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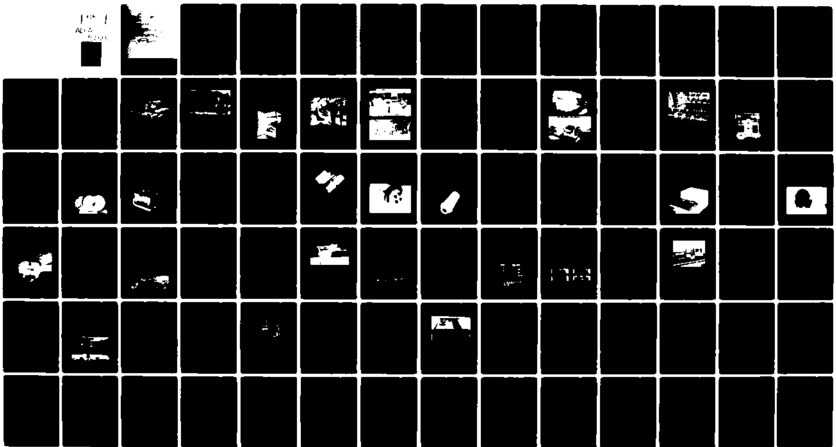

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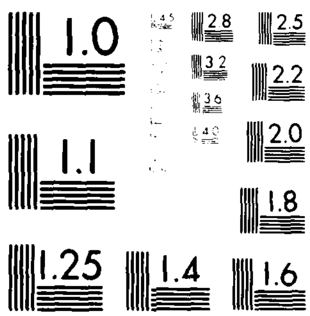


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**MCDONNELL DOUGLAS CORPORATION**

AFTS FINAL TECHNICAL REPORT OCTOBER 1981

This report was submitted by the McDonnell Douglas Astronautics Company, St. Louis Division, Missouri, 63166, under Contract F33615-7-C-1002 with the Space Division, Deputy, for Space Communications Systems, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. Capt Robert S. Mason, SD/YKXL was the project engineer.

This report has been reviewed by the Office of Public Affairs (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Project Engineer, LaserCom FLight Test Systems

FOR THE COMMANDER

WILLIAM J. FOSTER, Lt Colonel, USAF
Director, Advanced Space Communications
Deputy for Space Communications Systems

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The objective of the AFTS program was to demonstrate the operation of a full 1000 Mbps laser communications system transmitting from an aircraft to a ground station receiver. The system was designed around a spaceborne terminal requirements and included prototype operational components. The six years of contract activity included design of a spaceborne high data rate transmitter, adapting the space platform design to operate on a KC-135 aircraft, development and fabrication of both the ground based receiver terminal, and the airborne transmitter. In addition to hardware development an existing site at White

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Sands Missile Range was modified to accomodate laser communications equipment for test activities. Supporting the hardware development a series of 5 field tests (both airborne and ground to ground) were conducted to evaluate the field operation of system design concepts and actual hardware performance. The program culminated in a final field test conducted to fully evaluate the complete system which included autonomous acquisition, tracking, 10 pbs communications, 20 Kbps beacon communications, and 500 Mbps and 1000 Mbps downlink communications.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF ACRONYMS

| | |
|---|---|
| AFTS | Airborne Flight Test System |
| AGC | Automatic Gain Control |
| AOML-FD | Acousto-optical Mode Locker-Frequency Doubler |
| APD | Avalanche Photodiode Detector |
| APP | Angle Pointing Processor |
| ATP | Acquisition and Tracking Detectort |
| BER | Bit Error Rate |
| BERP | Bit Error Rate Processor |
| BPS | Bits Per Seconds |
| BRT | Brassboard Receiver Terminal |
| DCFP | Dynamic Crossfield Photomultiplier |
| DPA | Digital Processor Assembly |
| DRU | Data Recovery Unit |
| EFM | Engineering Feasibility Model |
| FTD | Fine Tracking Detector |
| GSTA | Ground Station |
| HDR | High Data Rate |
| HDRROS | High Data Rate Receiver Optical Subassembly |
| IOA | Imaging Optics Assembly |
| LPL | Lamp Pumped Laser |
| LSMU | Lasercom Space Measurement Unit |
| MAR | Multiple Access Receiver |
| NFD | Narrow Field Detector |
| OLP | Open Loop Pointing |
| PDBM | Pulse Delay Binary Modulation |
| PIM | Pulsse Interval Modulation |
| PN | Pseudorandom Noise |
| PPBM | Pulse Position Binary Modulatioin |
| PQM | Pulse Quaternary Modulation |
| SCADE | Signal Conditioning and Detection Electronics |
| SCFP | Static Cross-Field Photomultiplier |
| SFTS | Spaceborne Flight Test System |
| SPL | Sun Pumped Laser |
| TMBS | Torque Motor Beam Steerer |
| TT&C | Tracking, Telemetry & Control |
| WFD | Wide Field Detector |
| WSMR | White Sands Missile Range, New Mexico |

LIST OF PAGES

## 1.0 INTRODUCTION

The Lasercom Airborne Flight Test System (AFTS) program was directed toward the development and evaluation of critical components and design concepts applicable to a High Data Rate spaceborne laser communications system. These concepts were demonstrated over an experimental link between an aircraft and ground station receiver (Figure 1.0-1). The effort represents an intermediate milestone for future space applications. The developed technology will reduce the risk associated with operational system deployment.

**AIRBORNE FLIGHT TEST SYSTEM**

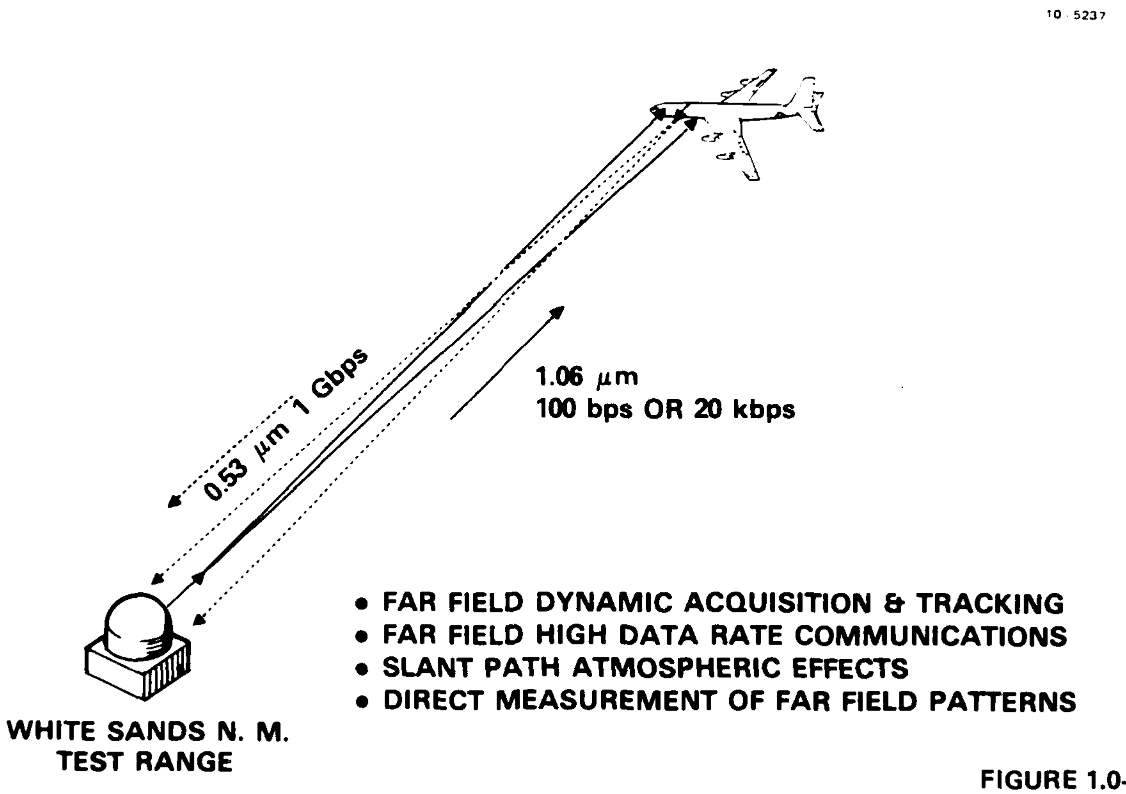


FIGURE 1.0-1

The primary objectives of this effort were:

(1) To demonstrate the transmission of data via laser from one location to another.

(2) To demonstrate that acquisition and tracking can be accomplished with narrow laser beams.

(3) To demonstrate and evaluate the inherent capabilities including jam resistance and covertness of laser communications, and

(4) To demonstrate these objectives with hardware based on space applicable principles.

The original program contract was awarded in the last quarter of 1975 as the Spaceborne Flight Test System (SFTS) program. Under the original program contract an experimental space to ground high data rate laser communications system was to be developed and the high data rate laser transmitter launched into a synchronous orbit in mid-1980. Since the laser transmitter is technologically more complex than the high data rate receiver, emphasis was placed primarily on development of the laser transmitter terminal for the space experiment rather than the high data rate receiver. The exception was the high data rate optical detectors [Dynamic Crossed Field Photomultiplers (DCFP's)], which were a new technology photomultiplier detector that was part of the receiver terminal. Under the SFTS program, space qualifiable DCFP units were to be built and flown with the SFTS transmit package to verify the space applicability of that design.

The SFTS system design and performance baseline was the outgrowth of the Engineering Feasibility Model (EFM) laboratory system development. With that system critical concepts such as laser operation, communications format, acquisition and tracking mode logic, and diffraction limited optical system design were developed and verified. Development of space qualifiable SFTS hardware was initiated based on EFM system design.

This development continued until late 1977 when reduced funding resulted in a change of scope from a spaceborne high data rate transmitter to an airborne high data rate transmitter. Although the airborne flight test approach was a much lower risk approach than the space flight system, airborne platform dynamics and low altitude atmospherics actually presented a more challenging application of Lasercom technology. To preserve commonality of design with spaceborne systems, the decision was made to limit changes to the original spaceborne package design. The approach taken was to add additional "platform unique" components to adapt the spaceborne package to the aircraft environment. Added components included an external telescope baffle to reduce the anticipated additional solar

scatter from the aircraft optical window, an additional acquisition detector (Multiple Access Receiver) to accommodate the larger open loop pointing uncertainties associated with aircraft to ground operation, and an auxiliary computer to process the signals from this detector as well as the platform position and attitude reference information. The resulting angle commands were transferred to the space prototype acquisition and tracking hardware and used in place of satellite ephemeris computations which would have been done by that equipment. With the exception of that interface no other significant changes were made to the initial spacecraft system design concept. In addition to preserving the original spaceborne configuration, several critical components developed under the SFTS program were retained as space prototype hardware in the current program. These included the 5 μrad diffraction limited telescope, the 1 Gbps optical modulator, the imaging optics assembly, the mode-locked frequency doubled high data rate lamp pumped laser, and the signal conditioning electronics for the acquisition and tracking detectors.

The communication, acquisition and tracking functions were accomplished by placing the high data rate transmitter in a KC-135 (Figure 1.0-2) and acquiring, tracking, and communicating with a receiver located in a domed building at the Cowan Site at White Sands Missile Range in New Mexico (Figure 1.0-3). The airplane flew a circular trajectory around the ground station at slant ranges from 10 Km to 100 Km.

The high data rate transmitter acquired and tracked a 1.06 μm beacon beam to obtain line of sight pointing information to the ground station for the high data rate transmitter. The high data rate transmitter transmitted a narrow (<100 μrad) 0.53 μm beam modulated with 1 Gbps Pulse Quaternary Modulation (PQM). Instrumentation was provided on the aircraft and at the ground station to measure acquisition and tracking times and accuracies; communications error rates; infer slant path atmospheric effects and make direct measurement of far field patterns via scanning of the transmit beam. The 1.06 μm beacon provided 100 bps and 20 kbps optical uplinks.

Finally, this report is intended to be an historical overview highlighting the significant accomplishments and findings of the AFTS/SFTS program. The details of

the evolution of design and hardware have been tracked through rigorous hardware and field test reports. The timeline shown in Figure 1.0-4 places the chronological significance to these various reports.

## C–135 LASERCOM TEST BED AIRCRAFT

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FIGURE 1.0–2

## WHITE SANDS FACILITY

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FIGURE 1.0–3

## AFTS PROGRAM TIMELINE

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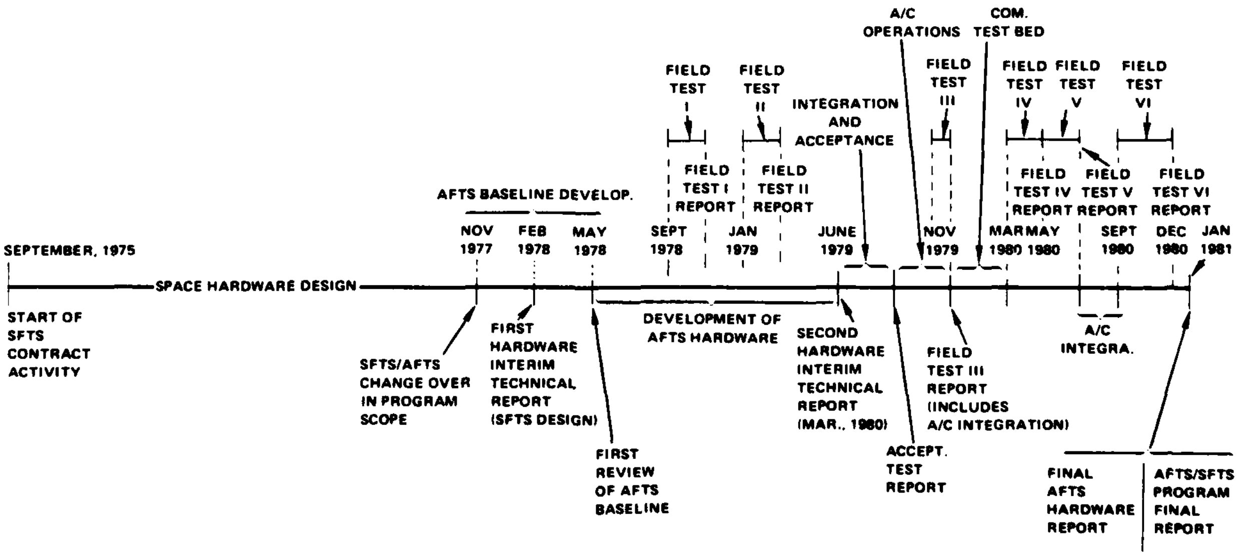


FIGURE 1.0–4

2.0 FLIGHT HARDWARE

The flight hardware is divided into an Electrooptic Assembly and an Electronic Assembly. The Electrooptic Assembly was installed in an environmental enclosure (Figure 2.0-1) which was located behind the cargo door; modified to mount a 30" optical window for transmission and reception. The Electrooptical Assembly was held by an isolation support structure which used a shock mount and a single point rotary joint for the optical assembly attach point to isolate the optical assembly from the platform vibration dynamics. The optical components were continuously purged with dry nitrogen during operation. In addition, the Electrooptic Assembly was placed inside an environmental enclosure which provided additional protection against contamination and produced temperature control by filtering, heating, and recirculating the air inside the enclosure. Electronic subassemblies were located

**ELECTROOPTICS ASSEMBLY AND SHROUD INSTALLATION IN C-135A**

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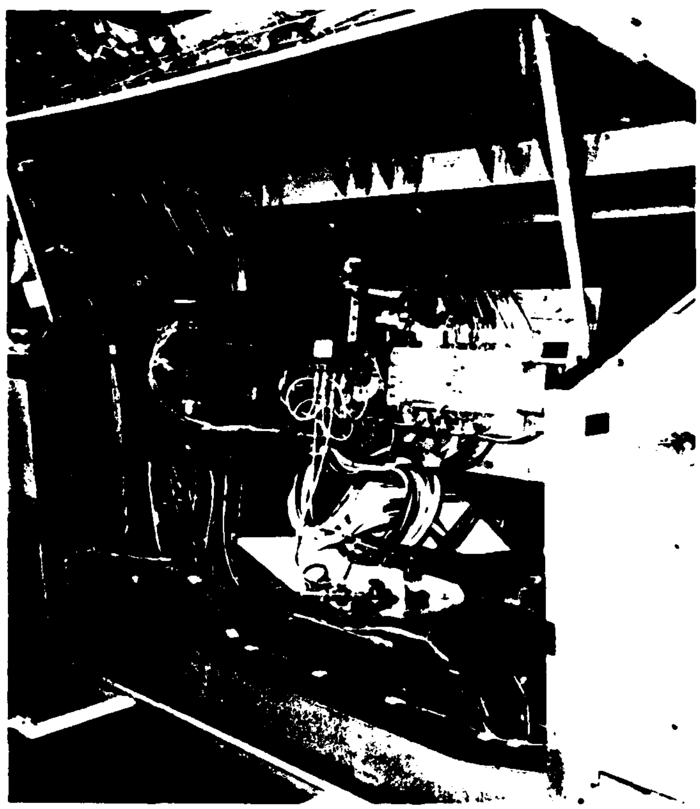

FIGURE 2.0—1

in five shock mounted racks installed parallel with the centerline of the aircraft (Figure 2.0-2). Overhead cable racks carried prefabricated cables between electronic racks and the Electrooptic Assembly.

LASERCOM CONSOLE INSIDE TEST BED AIRCRAFT

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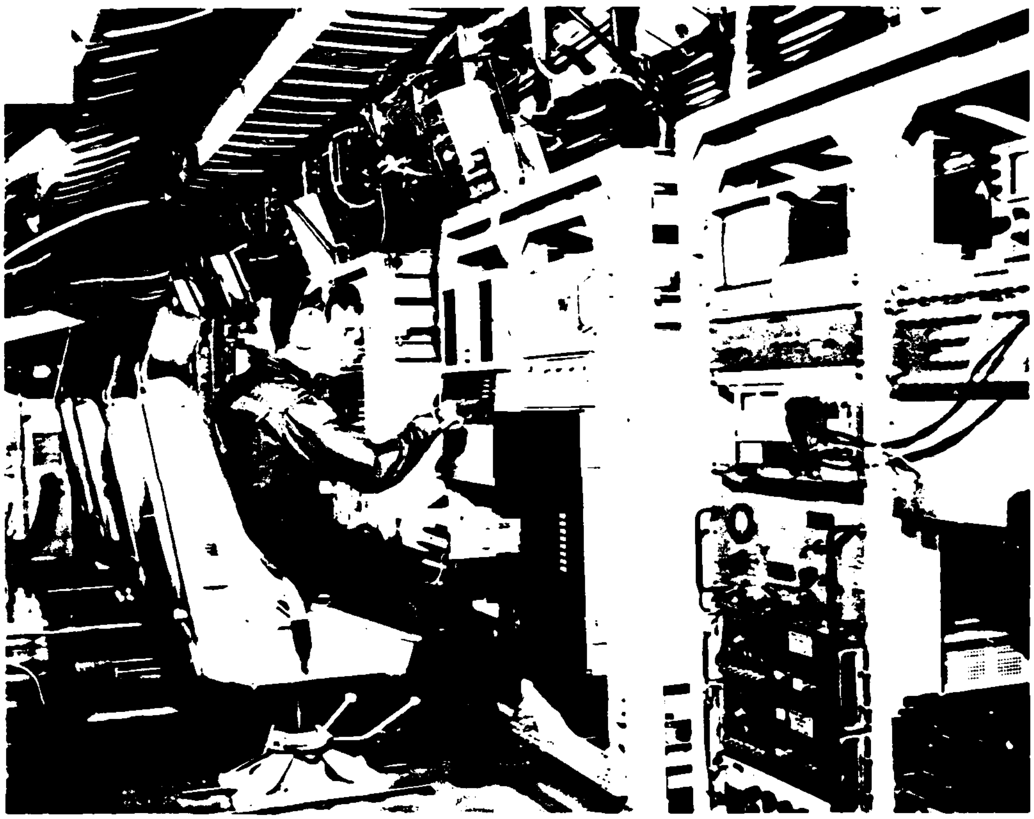

FIGURE 2.0–2

2.1 Electro-Optics Assembly

The AFTS Electro-Optics Assembly is shown in Figures 2.1-1 and 2.1-2. The various electro-optical components were mounted to this baseplate. The AFTS Electro-Optics consisted of the assemblies shown in Table 2.1-1.

Of these eleven assemblies, the baffle optics and acquisition monitor telescope were added to the electro-optics package spcecifically for the aircraft experiment. The Multiple Access Receiver (MAR) was added to function as a field of view acquisition detector to cover the initial aircraft pointing uncertainties and to

## AFTS ELECTROOPTICS ASSEMBLY (FRONT)

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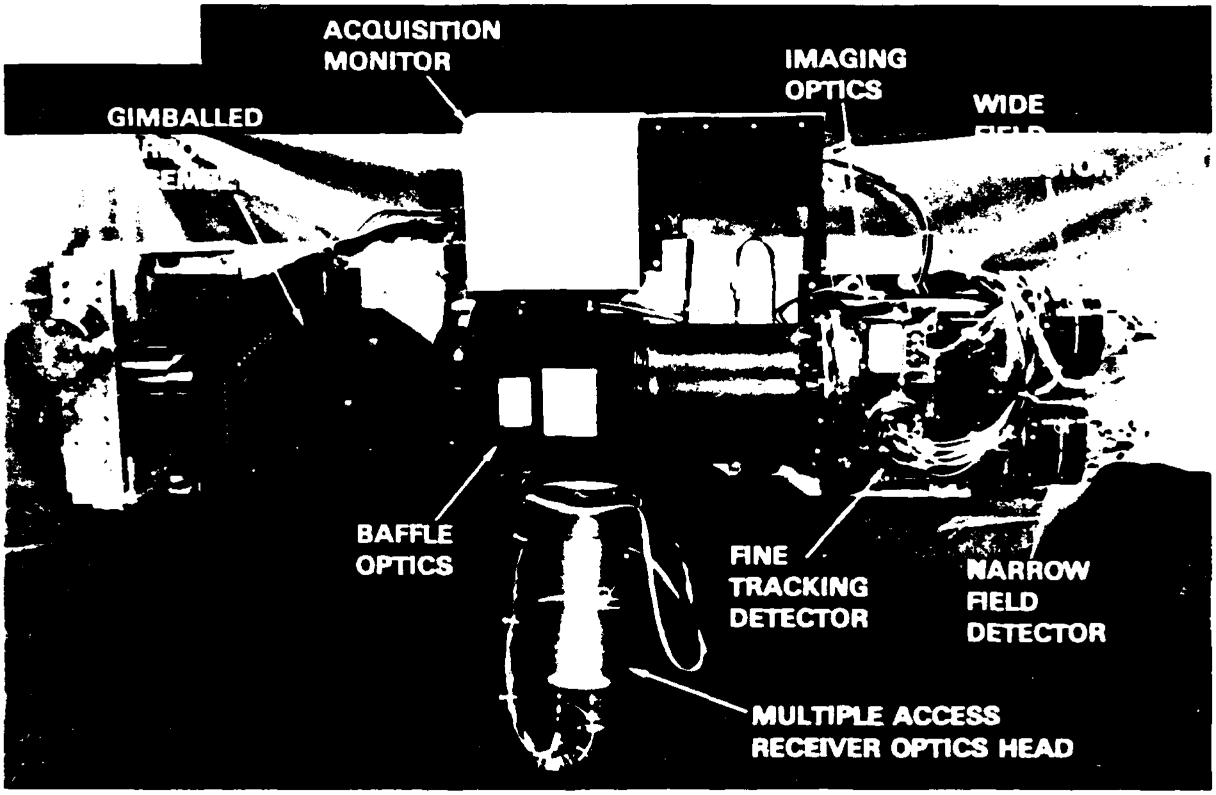


FIGURE 2.1–1

## AFTS ELECTROOPTICS ASSEMBLY (BACK)

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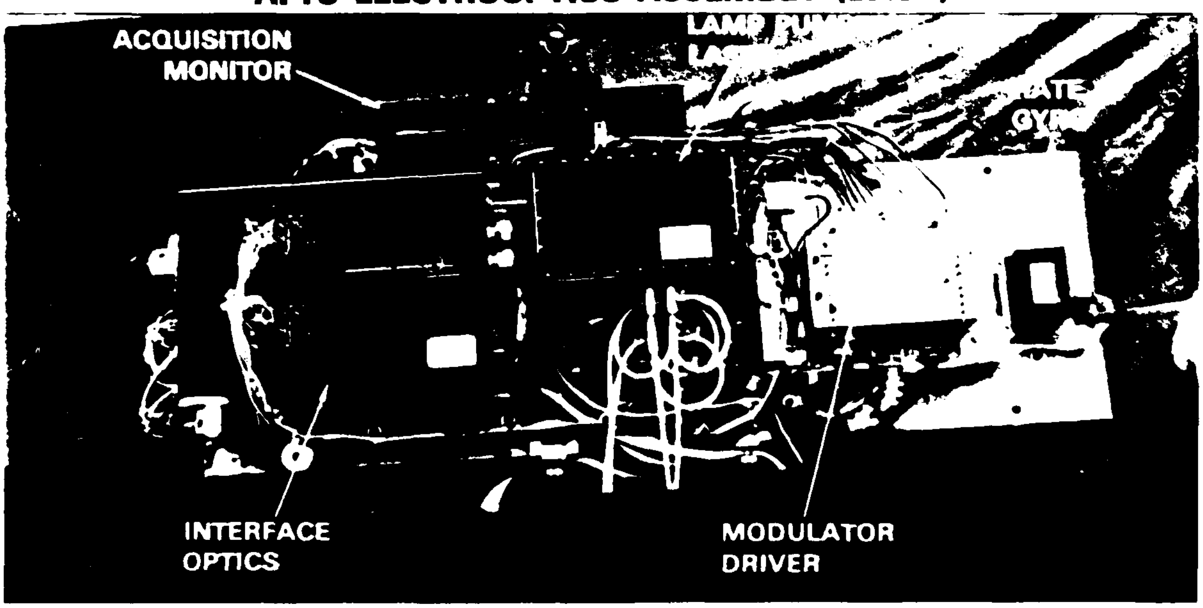


FIGURE 2.1–2

demonstrate the fundamental concepts of multi-user access required for many operational system applications. The remaining electro-optic functions were originally part of the SFTS baseline package. Some of these components were developed to space qualifiable hardware maturity, and all meet the performance requirements necessary for a 1 Gbps space to ground link or space relay crosslink. The most technically difficult components were selected as the candidates for space prototype development. Table 2.1-2 lists the AFTS components and their maturity.

Table 2.1-1 AFTS Electro-Optic Assemblies

| | |
|---|---|
| Laser | Telescope |
| Interface Optics | Baffle Optics |
| Modulator | Acquisition Monitor Scope |
| Imaging Optics | Multiple Access Receiver |
| WFD/NFD Acquisition Detectors | Gimballed Mirror |
| Fine Tracking Detector | |

### 2.1.1 High Data Rate Laser

The AFTS Lamp Pumped Laser (Figure 2.1-3) was developed as one of the two lasers that were to fly on the original SFTS platform. The primary SFTS laser was a mode locked, frequency doubled Nd:YAG sun pumped laser. This laser was pumped by solar energy collected from the large telescope in the solar collector assembly and precisely filtered to relay only the energy in the Nd:YAG pump bands to the laser. A breadboard sun pumped laser (Figure 2.1-4) was built and tested successfully in the laser test facility at the Cloudcroft Ground Station Complex. With 100W of solar input better than 400 mW of mode locked, frequency doubled output was obtained with 200 to 220 ps rise time.

The lamp pumped laser was intended to be used as a redundant laser and during periods of solar eclipse on the SFTS experiment package. This laser was efficiently pumped by a Rare Earth Metal arc lamp whose spectral emission was closely matched to the absorption spectra of the Nd doped rod (Figure 2.1-5). The developed Potassium Rubidium (KRb) lamp has demonstrated over 10,000 hours of life at full output. The on orbit lifetime goal for these lamps was specified at 3000 hours. Further development in materials and packaging of the lamp led to a pure potassium arc for even greater pumping efficiency. This 7th iteration pure potassium lamp is the type used throughout the final series of AFTS tests.

TABLE 2.1-2
AFTS EQUIPMENT

| EQUIPMENT | USAGE | CONSTRUCTION |
|---|---|---|
| Airborne Package | | |
| Electro-Optic Assembly | | |
| o Laser | Operational | Space Prototype[1] |
| o Interface Optics | Exp. Unique | Breadboard |
| o Modulator | Operational | Space Prototype |
| o Imaging optics | Operational | Prototype Design |
| o WFD/NFD/FTD | Operational | Prototype Design |
| o Telescope | Operational | Space Prototype |
| o Baffle Optics | Experiment-Only | Brassboard |
| o MAR | Operational/Exp. | Prototype Design[2] |
| o Gimballed Flat | Exp./Operational | Prototype Design |
| Electronics | | |
| o DPA | Operational | Prototype |
| o Analog drive assy | Operational | Breadboard |
| o Angle pointing processor | Experiment | Commercial |
| o APP Interface | Experiment | Breadboard |
| o Multiple access receiver pro... | Experiment | Breadboard |
| o Laser control electronics | Operational | Breadboard |
| o Modulator compensator | Operational | Breadboard |
| o Modulator power supply | Operational | Breadboard |
| o Modulator drivers | Operational | Prototype |
| o High data rate comm elec | Operational | Brassboard |
| o Laser power supply | Operational | Commercial |
| o Power control units | Operational | Commercial |
| Tracking Ground Station | | |
| BRT Optics | | |
| o Acquisition and tracking det. | Operational | Commercial |
| o Optical interface | Operational | Breadboard |
| o Beacon laser | Operational | Commercial |
| o Call-up laser | Operational | Commercial |
| o High data rate receiver | Operational | Brassboard |
| o Telescope | Experiment | Brassboard |
| o Gimbals | Experiment | Breadboard |
| BRT Electronics | Experiment | Breadboard |
| HDR Comm. Electronics | Operational | Brassboard |

Notes:

1. Although the laser performed operational functions and is suitable for airborne terminals, the envisioned spaceborne operational laser will utilize diode-pumping for longer life and greater efficiency.

2. The MAR was incorporated into the AFTS to accommodate the larger acquisition uncertainty region associated with the air-to-ground experiment. The residual multiple access and communication capabilities have operational relevance on other lasercom systems (not necessarily a high data rate sync-to-ground or sync-to-sync link).

# AFTS LAMP PUMPER LASER

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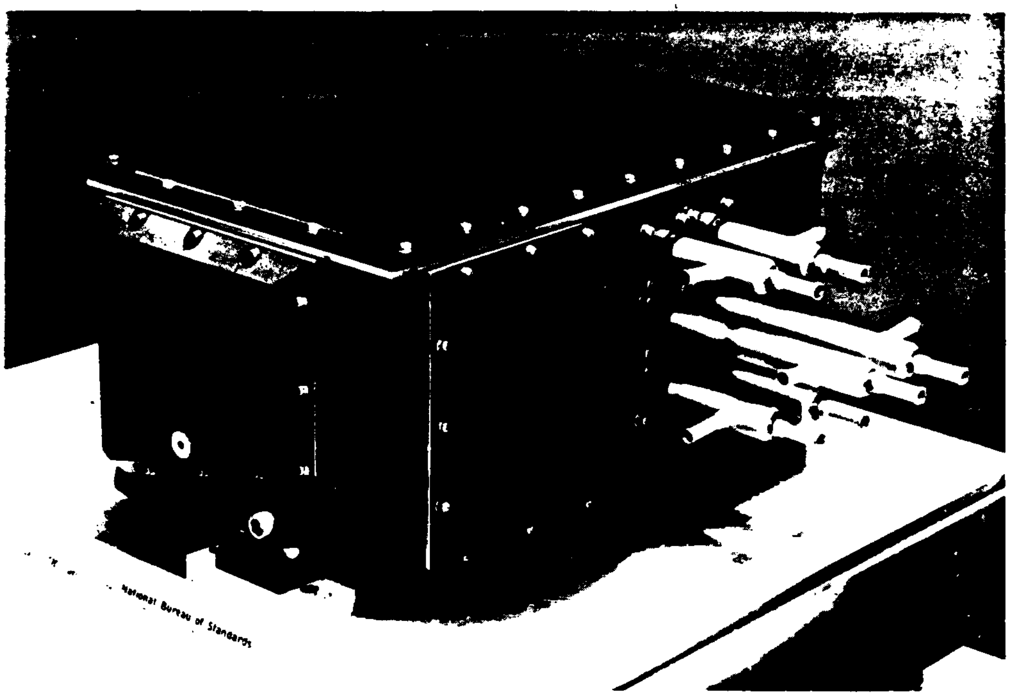


FIGURE 2.1–3

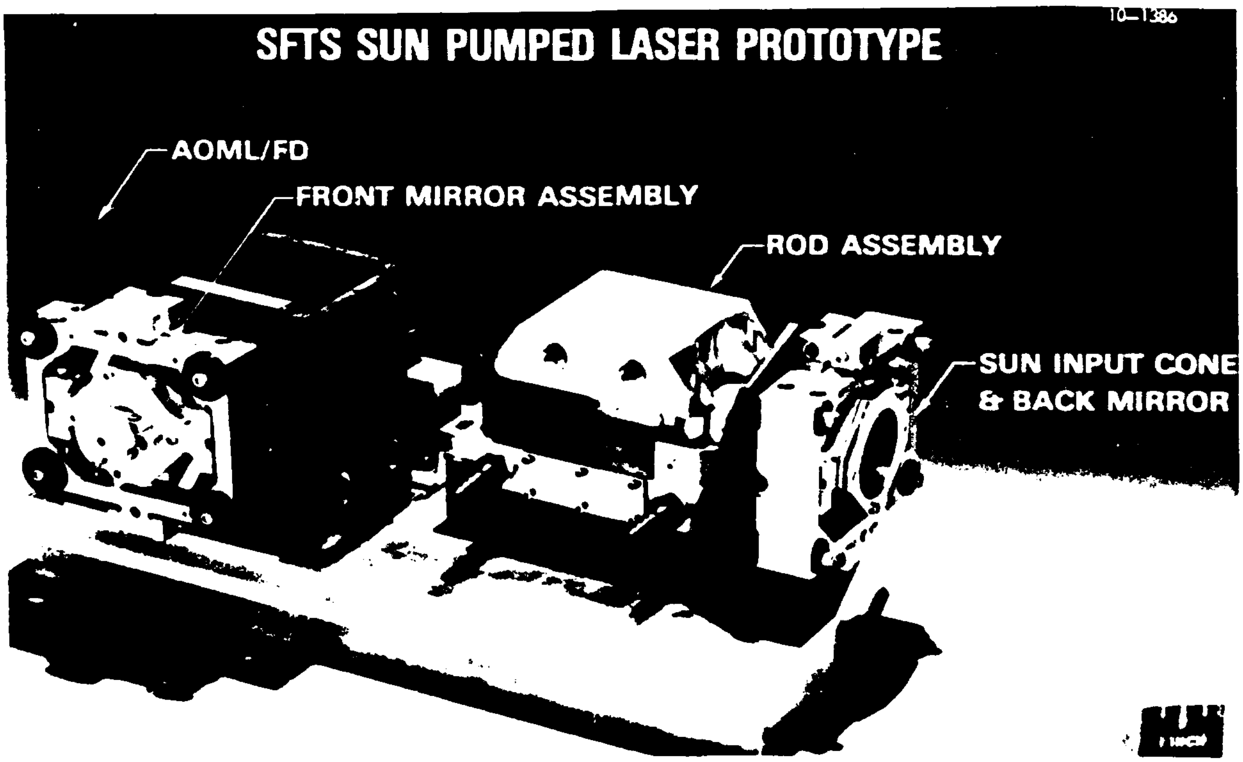




FIGURE 2.1–4

# K-Rb PUMP LAMP EMISSION SPECTRUM

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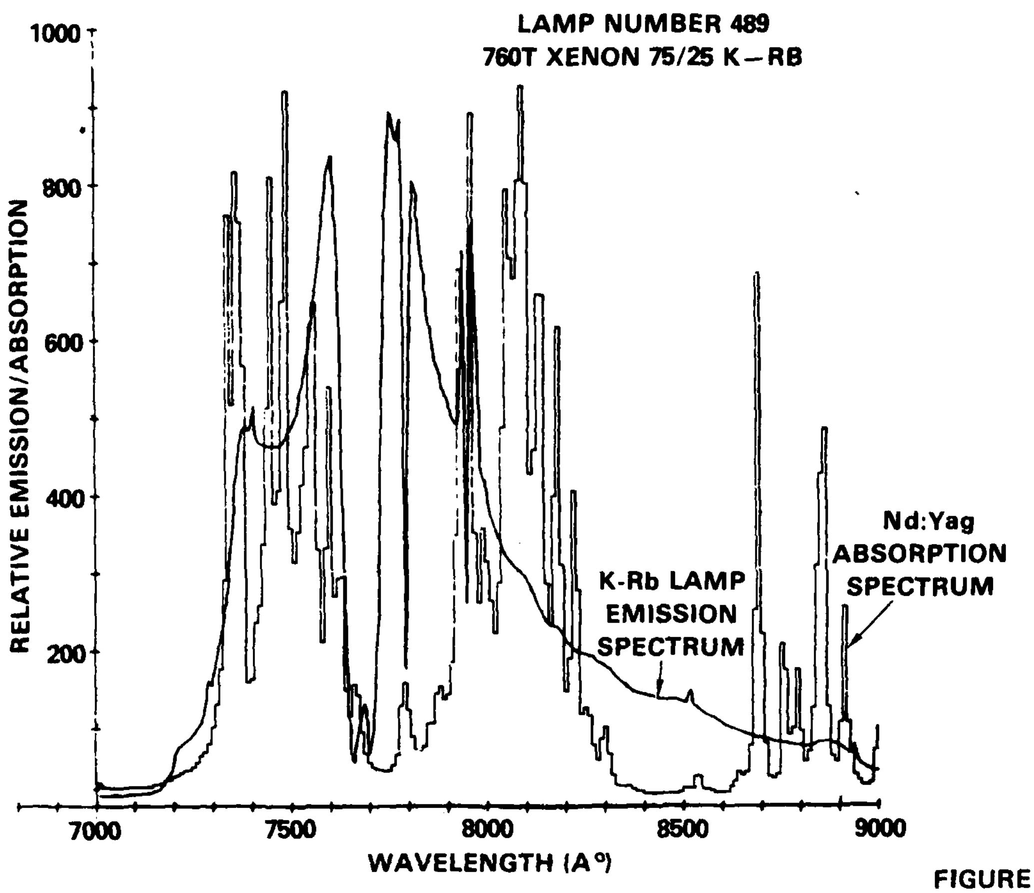


FIGURE 2.1-5

To provide an accurate evaluation of lamp life it was necessary to perform the life testing in a simulated zero-g environment. This was required to provide realistic wall temperatures. To this end a life test facility (Figure 2.1-6) consisting of 20 test stands was assembled at MDAC-STL. Each station consisted of a test cavity with a dielectric cylindrical insert that controlled the envelope temperature to the zero-g levels. It also contained a glass purge enclosure connected to a dry-nitrogen purge. Automatic power supplies provided the capability for automatic ignition, constant power operation, and extinction of each of the 20 lamps.

## LAMP LIFE TEST FACILITY

10-9133

FIGURE 2.1–6

Both the SPL and LPL are of a folded cavity design for compactness and improved doubling efficiency. Both lasers utilize a single intracavity device for acousto-optic mode locking and frequency doubling. This device known as the AOML-FD is a $BaNaNiO_3$ crystal driven with an acoustic transducer at 250 MHz and thermally stabilized at the phase matching temperature. The LPL is a hermetically sealed space prototype design, portions of which were tested to space launch environments to insure mechanical stability. Typical operating performance during the field operations was 180 mW average output power for 250 watts of prime pump power and 350 ps pulse width. These output parameters are the same as would be required for the intended space applications, although new technology laser diode pumping significantly reduces the prime pump power for the same performance.

2.1.2 High Data Rate Modulator

The AFTS High Data Rate Modulator uses a combination of polarization binary modulation and time delay binary modulation in a patented format known as Pulse Quaternary Modulation to achieve a 1 Gbps channel bandwidth from a 500 Mpps laser source. The modulator (shown in Figure 2.1-7) consists of two separate polarization modulators. Time delay modulation is accomplished by selectively passing the optical pulse through a 1 ns passive time delay unit. The output is then run through a second polarization modulator. Each modulator section uses Lithium Tantalate crystals driven as a lumped parameter with a 22 $V_{p-p}$ Drive waveform. In addition to the full 1 Gbps channel capacity each modulator may be driven separately for 500 Mbps PDBM or PPBM modulation formats. This component also is space prototype hardware with selected elements tested to launch and space environments.

MODULATOR

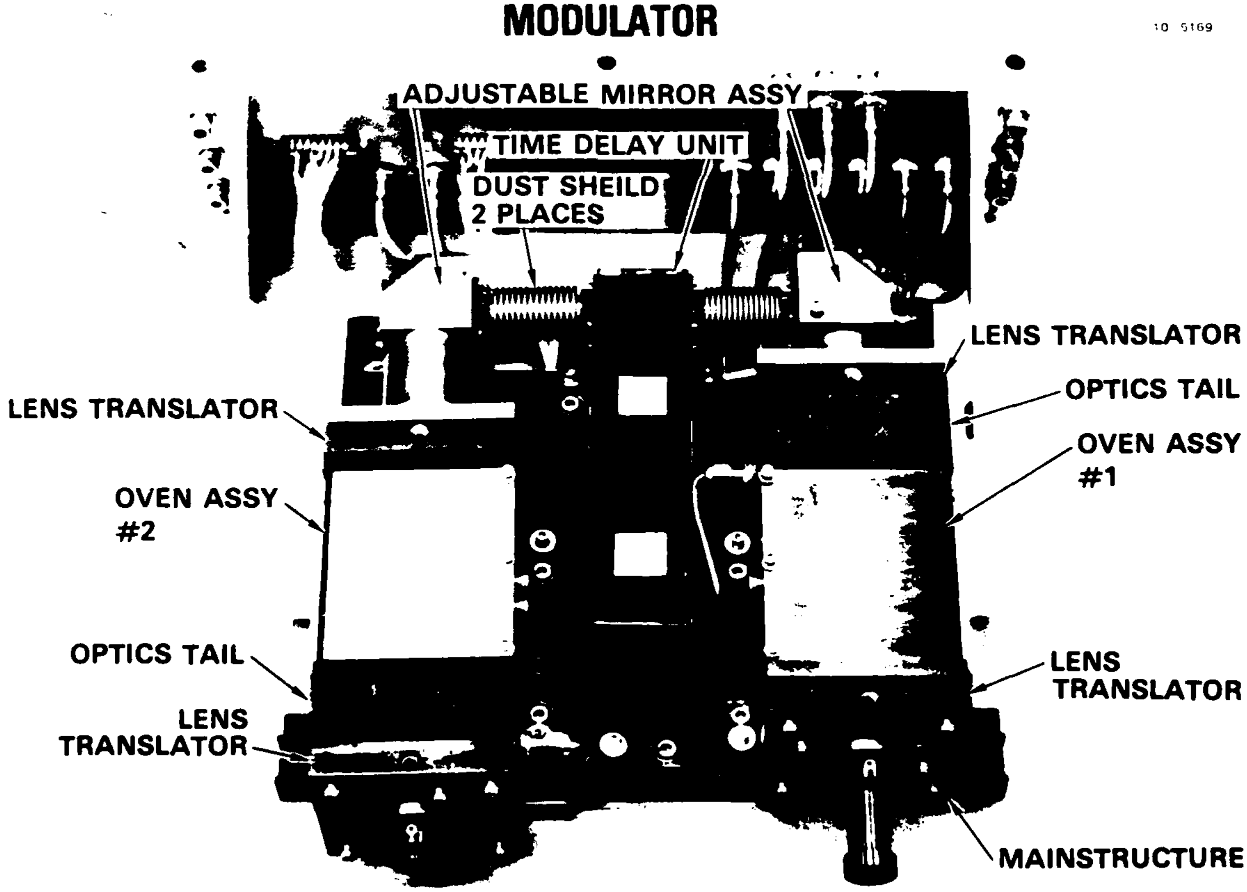


FIGURE 2.1–7

The measured transmission for the entire modulator assembly on AFTS was 70%. This is greater than the budgeted transmission required for the space applications. To meet the required communication efficiency on space borne operational links better than a 20:1 dynamic extinction ratio is required. This extinction ratio has been demonstrated on the Engineering Feasibility Model. Currently the Polarization modulator (which is the most demanding in performance) operates with a 20:1 extinction ratio, with the first modulator operating at better than 15:1 extinction ratio. This more than satisfied AFTS experiment requirements. Further work to retrofit the first modulator with one capable of 20:1 extinction ratio or AFTS was not warranted. As with the laser pump lamp, extensive accelerated life testing has been done on the coated crystals to insure transmission stability. To date transmission has remained stable with over 750 hrs of exposure to 1.25 MW $cm^{-2}$ of optical power, which is 65 times greater than operational levels, and also after exposure to over 3100 hrs of operational temperatures.

### 2.1.3 AFTS Interface Optics

The AFTS laser/modulator interface optics (Figure 2.1-8) functional requirements were driven by the specific electro-optic assembly layout rather than spaceborne application requirements. As such this assembly was built as brassboard hardware to provide the optical path between the laser and modulator and to direct light out of the modulator and into the imaging optics assembly. In addition to the static alignment capability, a closed loop dynamic angular alignment capability was added to maintain angular alignment between the laser and modulator. Motor driven optical cubes were included to allow the capability to adjust beam decenter into the modulator via remote control.

### 2.1.4 Imaging Optics Assembly

The AFTS Imaging Optics Assembly (Figure 2.1-9) performs the functions of receiving the 1.06 μm beacon illumination and relaying it through various optical paths to one of the acquisition or tracking detectors. It also shapes and directs the 0.532 μm transmit beam down a coincident optical path. This piece of space prototype hardware boasts a complex optical design which included all functions including redunant functions in a small volume.

## AFTS INTERFACE OPTICS

10-5174 A

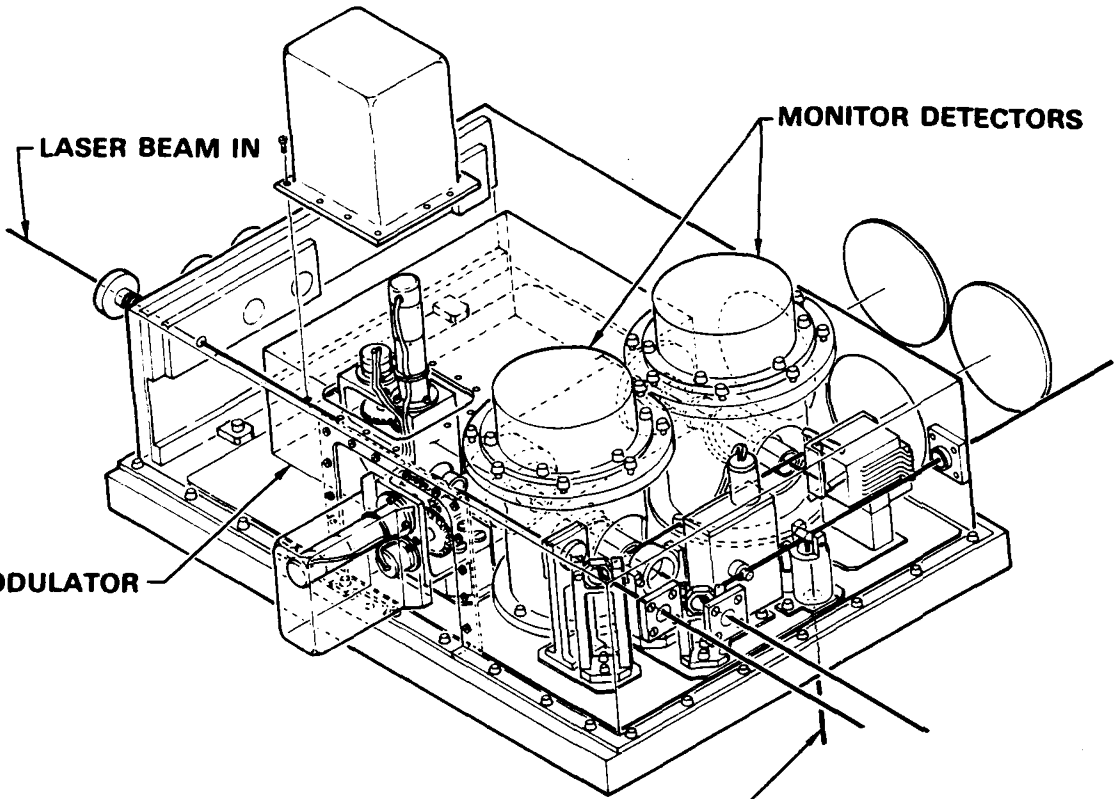


FIGURE 2.1-8

Depending on the mode selected, the IOA transmit either a diffraction limited 5 μrad beam full aperture, or a decentered, spoiled 100 μrad beam. An adjustable focus of the 5 μrad beam to allow beamwidth adjustment between 5 μrad and 40 μrad. An automatic static alignment path is included which utilizes parasitic losses in the diplexer dichroic to align the noncommon portions of the transmit and receive optics. Although not required on the airborne experiment, a "point ahead" function is included to introduce a carefully calibrated pointing bias between the transmit and receive functions to correct for on orbit velocity of light aberration.

Three distinct receive paths are incorporated into the IOA for acquisition and tracking of the 1.06 μm beacon. The Wide Field Acquisition Detector (WFD) field of view is ±0.15°. This is the field required to cover the initial pointing uncertainties of a geosynchronous satellite pointing to another geosynchronous satellite or a ground terminal. The Narrow Field Acquisition Detector is the second detector used in the acquisition sequence to further reduce optical pointing errors and prepare for fine tracking. The field of view of the NFD was increased from ±500 μrad to ±750 μrad on the aircraft experiment to accommodate possible larger platform dynamics during acquisition. Separation between the WFD and NFD viewfields is accomplished by means of a bifurcating mirror at the telescope image plane. Both acquisition paths relay the beacon signal to quadrant arrays of avalanche photodiodes for processing of angle information. Dividing of the various image planes is accomplished with a precision pyramid to split the plane into quadrants and very fast aspheric optics (f/0.9) to focus the energy onto 0.8 mm Avalanche Photodiode Detectors (APD). Because of the sensitivity of the APD's to optical background illumination a three cavity 50 Å @ 1.064 μm interference filter was developed to reject a significant amount of optical background.

## IMAGING OPTICS ASSEMBLY

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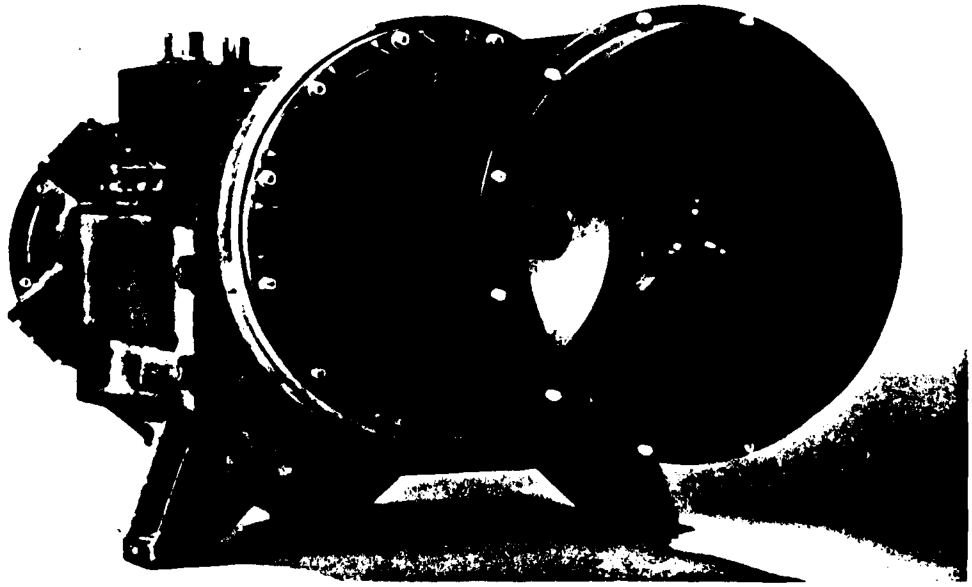

FIGURE 2.1–9

The optical design incorporated radiation resistant elements and coatings. Redundancy was also included to preclude the occurrence of single point failures. Confirming the space qualifiable design values, the Imaging Optics Assembly including the telescope had better than an 85% transmission on the 5 μrad transmit path, and better than 68% transmission on the FTD receive path.

Precision 300 Hz tracking loops were required to support the pointing of the 5 μrad beam in the presence of spacecraft dynamics. Special beam steering devices were developed. These were small, light-weight torque motor devices which turned low inertia fold mirrors (Figure 2.1-10). These Torque Motor Beam Steerers (TMBS) were equipped with precision position feedback for tracking loop compensa-

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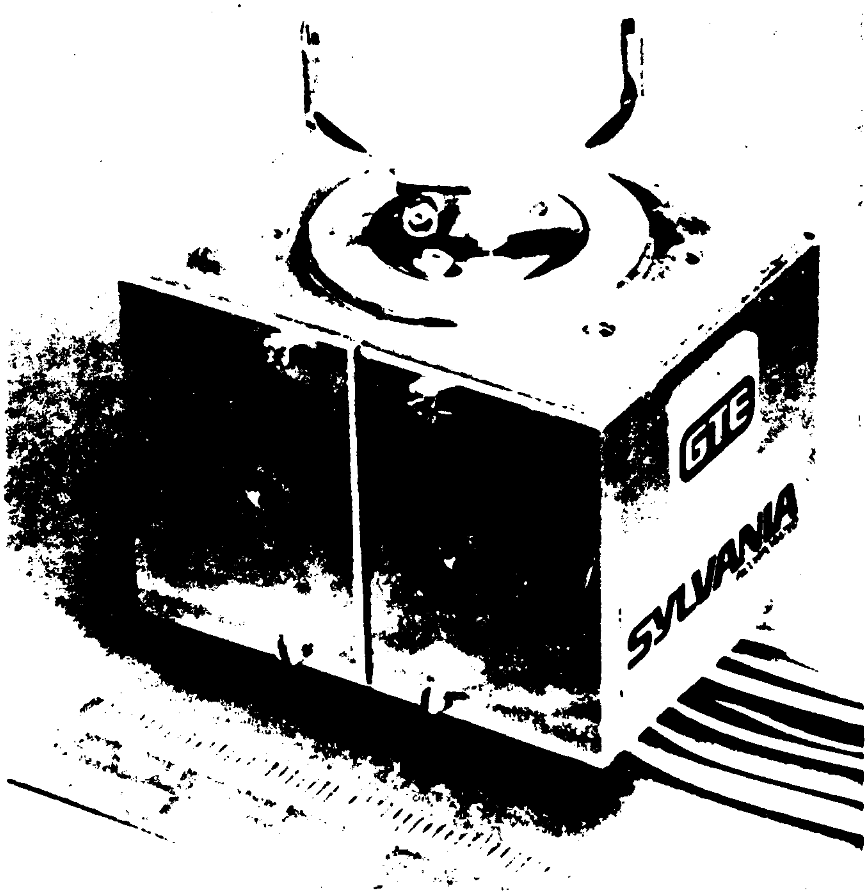



**TORQUE MOTOR BEAM STEERER**

**FIGURE 2.1-10**

tion. During the flight experiments these devices tracked at bandwidths out to 300 Hz with an accuracy less than 0.6 μrad, 3σ in the laboratory.

2.1.5 AFTS Telescope

The AFTS telescope was designed and developed under the SFTS program. Because of the critical performance requirements and precision required to meet those requirements, this unit was developed as space qualifiable hardware even after the program was rescoped. The Cassegrain telescope clear aperture is 0.191 m and the central obscuration 0.046 m. To support the required antenna gain efficiency an extremely precise wavefront quality was required from the telescope. The measured value for this telescope was λ/50 @ 0.532 μm making it one of the highest quality small aperture Cassegrain telescopes ever built.

During the course of development an extensive analysis was performed to determine the telescope performance in the presence of the on orbit thermal environment. At the conclusion of this study it was determined that the original all beryllium baseline configuration was intolerant of the thermal gradients induced by on orbit sun loading. Although it was possible to build an all beryllium telescope that would perform under sun loading, it was thought that continuing with the all beryllium design could adversely impact both cost and schedule.

An alternative design using Invar spider and barrel and Cer-Vit optics evolved which was readily capable of meeting performance requirements in the presence of the anticipated orbital sun loads by the addition of a simple thermal insulation around the inside of the barrel. Although this was a somewhat heavier telescope (18 lbs for the Invar and Cer-Vit as opposed to 5 lbs for the beryllium) it was decided that this design was a lower risk approach to achieving the system performance.

The space qualifiable prototype telescope has silver reflective coatings with a silicon dioxide protective overcoat. The measured transmission is 98% at 1.064 μm and 88% at 0.532 μm. Internal knife edge baffling with Martin-Black® anodizing over the complete interior surface was added to minimize stray light scatter and improve off axis rejection. Consistent with the original spaceborne system

requirement the measured telescope wavefront quality was better than $\lambda/50$, rms attributing to less than 0.07 dB of on axis loss in the diffraction limited 5 μrad transmit beam.

### 2.1.6 Acquisition and Tracking Detectors

To perform the functions of acquisition and tracking with the 1.064 μm ground station beacon, the AFTS (and SFTS) used a progressive acquisition and tracking handover sequence which employed two acquisition detectors [Wide Field Detector (WFD) and Narrow Field Detector (NFD)] and a Fine Tracking Detector (FTD). Using a technique analogous to the mono-pulse processor in conventional RF radar systems, each of those detectors used a quadrant array of photosensitive elements which were ratiometrically processed to derive very precise angle information. To pass the very narrow (100 ns) pulses from the Q-switched beacon laser, the detectors were required to have an electrical bandwidth of 3.5 MHz. The performance of those assemblies was driven by maximum sensitivity for the acquisition detectors, and by accuracy and stability for the tracking detector. To accommodate the two sets of requirements, two separate concepts were implemented. The acquisition detector used a discrete array of Avalanche Photodiodes (APD's) which were optimized for sensitivity at the fundamental Nd:YAG wavelength, and the Fine Tracking Detector used silicon P-I-N quadrant diode which was closely matched and coupled to extremely low noise high gain bandwidth transimpedance amplifiers for optimum tracking performance.

The original acquisition detectors used in the SFTS design was a specially developed InGaAsP (or III-V) ruggedized photomultiplier tube (Figure 2.1-11). This device had quantum efficiencies on the order of 2% to 5% (compared to S1 PMTS with <0.1%) at 1.064 μm. A theoretical detection performance (90%) was achieved for 7 PE/pulse in the EFM system which corresponds to 1.5 nW, peak pulse power incident on the quadrant array. Although these devices easily met the SFTS sensitivity requirement, it was necessary that they be maintained at a constant -20°C at all times, operating and nonoperating, to preserve quantum efficiency. Aside from the weight burden of supplying special heat pipes and special redundant thermal control systems there were the attendant difficulties of maintaining this temperature at both prelaunch and during the power critical launch and insertion periods.

# III–V ACQUISITION PMT

10-9139

FIGURE 2.1–11

Fortunately, soon after the SFTS program had commenced, Avalanche Photodiodes (APD's) were developed with very low ionization coefficients which promised to be capable of achieving sensitivity comparable to the III-V's. The result of the ensuing development were special high performance silicon APD's. These devices were made thick to maximize the quantum efficiency in the transparent silicon. To compensate for the thickness the active area was reduced to reduce bulk noise and device capacitance. The result was a low noise device of 35% quantum efficiency and usable at high avalanche gains. These devices demonstrated the required detection performance (90% detection probability and unity false alarm rate) with less than 2 nW of peak pulse power. With only a slight sacrifice in sensitivity the APD offered enormous advantages in size, weight, and power and was incorporated into the SFTS system for both the WFD and NFD. Further improvements in sensitivity and weight reduction were achieved by incorporating a hybrid preamplifier

into the detector package itself. The final AFTS brassboard design was a complete detector assembly (Figure 2.1-12) consisting of four APD's and hybrid preamps followed by a dual gain post-amplifier to achieve the required dynamic range.

2.1.7 Multiple Access Receiver

During its survey of potential users of optical communications systems, McDonnell Douglas determined that there was a need for a low data rate spaceborne receiver which could be simultaneously accessed by multiple users. The MDAC proprietary Multiple Access Receiver (MAR) concept was designed either to relay "report back" messages from various ground based or mobile units or to receive "call-up" requests for a high data rate optical communications relay link to a spaceborne terminal.

**AFTS ACQUISITION DETECTOR (WFD/NFD)** 10-9138

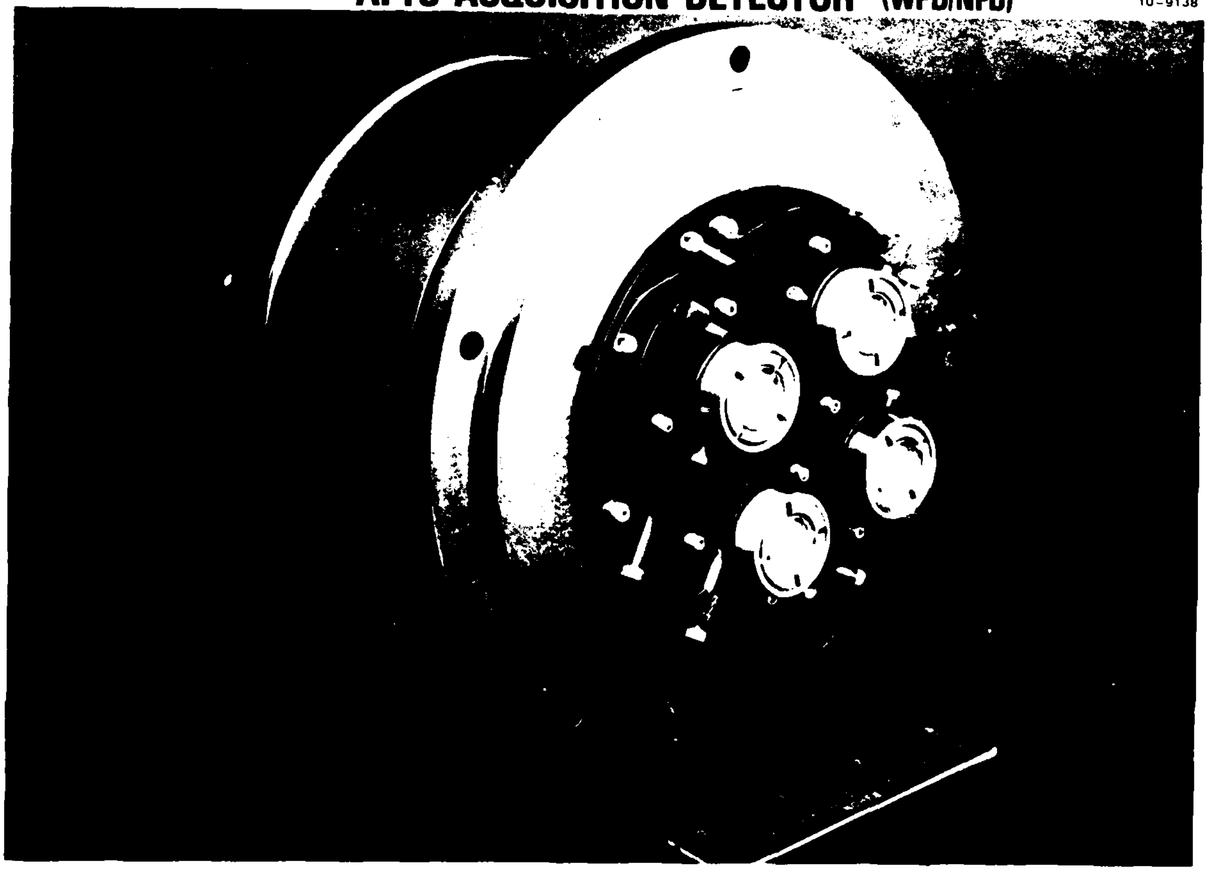


FIGURE 2.1-12

When the experiment platform was changed from a spacecraft to an aircraft, a larger viewfield acquisition detector was required to accommodate the increased open loop pointing uncertainty of the radar derived position information. To preserve the original spaceborne optics package design, the decision was made to add a third acquisition detector in front of the original package that could accommodate the larger viewfield. The MAR, being a small aperture large field of view detector, was well suited to meeting the AFTS requirement for acquisition. In addition, low data rate PIM communications electronics were added to demonstrate the communications capability.

A protype design version of the MAR (Figure 2.1-13) was added to the AFTS electro-optics package which used a 16 element APD array to cover the ±2° uncertainty field of the airborne platform. Although not space qualifiable (a space qualified version of the MAR has been built for the LSMU), all performance characteristics of an operational Multiple Access Receiver were met with this unit.

**MULTIPLE ACCESS RECEIVER**

10-3036

FIGURE 2.1–13

### 2.1.8 AFTS Gimbal

The AFTS gimbal is a prototype design. A number of advances were incorporated into this hardware that are applicable to space qualifiable systems. The most significant advance from the EFM implementation was replacing the optical shaft encoders with Inductosyn® high resolution resolvers. These devices had the advantages of high reliability, light weight, and increased precision. With the Inductosyns it is possible to point the gimballed mirror with an accuracy and resolution consistent with spaceborne system requirements for open loop pointing and acquisition.

The second advance was implementation of fully digital control compensation. The EFM control loops were a hybrid of analog and digital circuits. For AFTS, however, the entire gimbal control loop compensation as well as the system mode logic was incorporated into a single microprocessor in the Digital Processor Assembly electronics (itself a space prototype design), demonstrating for the first time in laser communications a high bandwidth, high resolution, digital servo control system.

## 2.2 Flight Electronics

The airborne electronics are grouped into three separate categories: (1) those functions required to support the SFTS spaceborne package, (2) the functions required to adapt the SFTS package to the airborne platform, and (3) instrumentation, diagnostic, and data acquisition equipment necessary to support the flight experiments. For the most part development of space qualifiable electronic hardware was viewed as a straight forward evolution of hardware developed during the Engineering Feasibility Model and earlier programs. For this reason, most of the electronics packages were developed as breadboard or commercial hardware to reserve resources for the development of the electro-optic assembly space prototype hardware. There were, however, two exceptions to this design philosophy.

The Digital Processor Assembly (DPA), which, because of a number of diverse requirements and stringent power and weight limitations required special emphasis to demonstrate that such a unit could be built within the demanding limitations of a spacecraft platform. The other component was the high data rate communications electronics (both transmitter and receiver). Like the DPA, the communications

electronics were under stringent size, weight, and power constraints for space applications. Additionally, the existing EFM hardware exhibited a strong temperature dependence on performance which was unsuitable for the aircraft experiment environment. For these two components the development started under the SFTS program was pushed forward under AFTS to yield a space prototype units.

### 2.2.1 Digital Processor Assembly

The Digital Processor Assembly (DPA) is central to the acquisition and tracking functions of the AFTS transmitter. In addition to processing the signals from the acquisition and tracking detectors and supplying the commands to the gimbals and TMBS's, the DPA contained the mode logic necessary to sequence through the various steps of acquisition and tracking as well as to supply the communications electronics with mode signals to commence communications once the system was locked in stable tracking. The DPA contained both analog and digital electronics to perform the functions shown in Table 2.2-1.

Table 2.2-1 DPA Functions

Signal Conditioning and Detection (SCADE)
Ratiometric Angle Processing
Gimbal Control Loop Compensation
Orbital Pointing Calculations Based on Ephemerides (SFTS Only)
Gimbal Drive Motor Commutation
TMBS Loop Command
Electro-Optic Assembly Mode Select
Mode Logic Control
TT&C

To preclude the occurrence of single point failures in both the spaceborne and airborne systems, redundancy mode logic was included to allow interchangeability of detector functions, and select alternate optical paths. Finally, a threshold optimization algorithm was built into the unit to maintain optimum acquisition and tracking detector sensitivity in the presence of varying day/night backgrounds and to compensate for component aging.

Each of these functions represented an advancement from the EFM hardware. The SCADES were required to demonstrate greater sensitivity with optical pulses of half the width of the EFM system. This required the incorporation of extremely low noise, high bandwidth circuitry and sophisticated electronic design approaches. Greater accuracy and repeatability was required from the angle processor which required the use of an internal auto-calibration between each received optical pulse. The mode logic not only contained more steps to incorporate the various ground station modes but was required to accommodate operator interaction to override or change any step. The threshold optimization routines, open loop pointing calculations, telemetry, and redundancy functions were completely new additions to the original EFM DPA implementation.

Because the requirements on the SFTS/AFTS DPA were more advanced than those of the EFM, completely new design approaches were required for almost every function. In order to improve sensitivity and facilitate redundancy, the EFM concept of a common ratiometric angle processor was changed to three discrete angle processors, each dedicated to a specific detector SCADE. This allowed for better alignment and matching of each SCADE/angle processor unit as well as complete functional redundancy between all three detector inputs. (This provided the capability of using any detector for any of the acquisition and tracking functions.)

To reduce power and facilitate optimization of the gimballed mirror control, the gimbal control loop compensation was changed from a discrete analog control loop to a full digital control system. This allowed individual adjustment of each of the many control loop parameters in software for best gimbal pointing performance. And finally because of the required mode logic flexibility with manual intervention the mode logic control was changed from the dedicated state logic of the EFM to a fully programmable software implementation. In this respect the DPA represents several "firsts" in lasercom development. It was the first implementation of a completely digital software gimbal control loop as well as programmable mode logic allowing on line operator intervention on mode logic flow.

The DPA was built around two microprocessors, one was used as an auxiliary processor to perform the necessary trigonometric transforms, and the second was the main processor which contained both gimbal control compensation and mode logic control

in one program loop. Telemetry capability was incorporated by user selection any eight of the many software resident variables to be dumped into a multiplexed IO port. These ports were updated on each program pass (200 passes/second). Processor command was implemented in a similar manner.

The unit built and flown in the AFTS equipment package met all of the SFTS functional requirements and performance goals (Figure 2.2-1). The only deviation from the SFTS configuration was substitution of open loop pointing commands from the angle pointing processor in place of the on orbit open loop pointing computation based on orbit ephemerides. However, the computer and memory were sized to be compatible with the computational requirements. The delivered ruggedized package was commensurate with spaceborne size, weight, and power allocations.

## DIGITAL PROCESSOR ASSEMBLY

10-9136

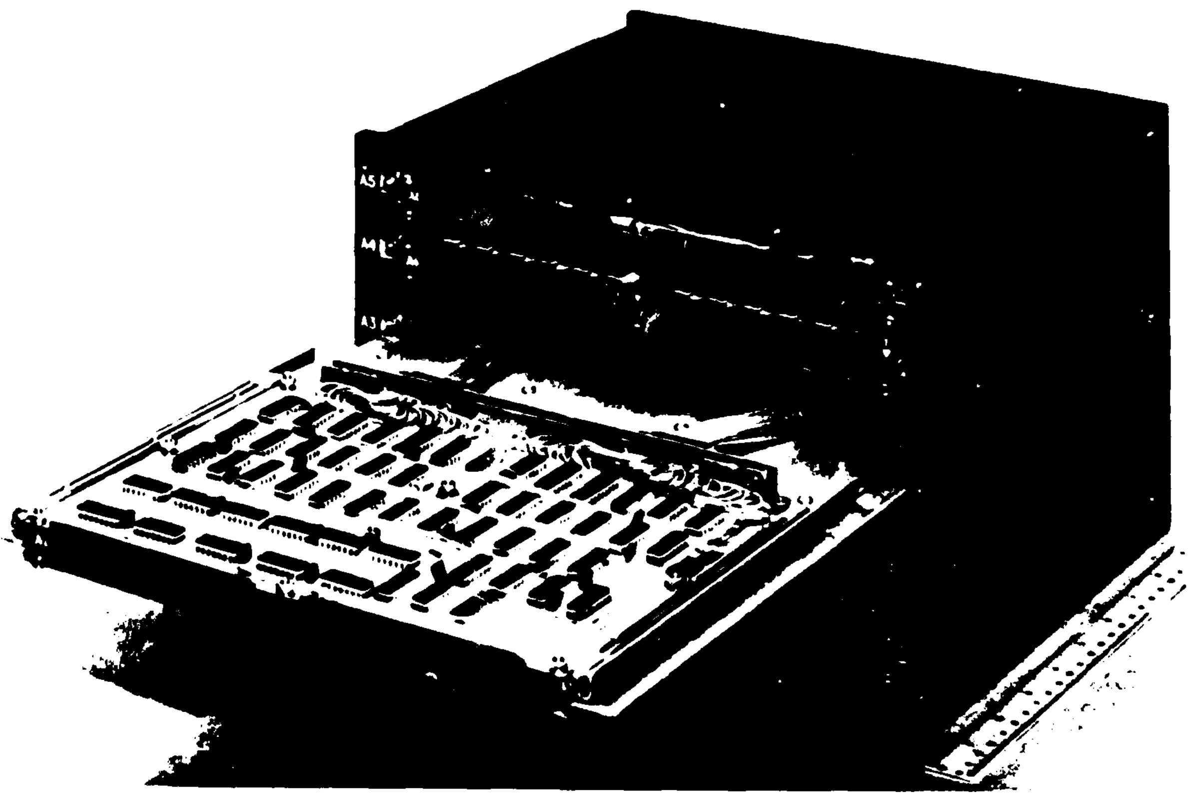



FIGURE 2.2-1

2.2.2 High Data Rate Communications Electronics

These electronics were also developed as space prototype equipment. Although similar in function to the electronics used in the EFM, a number of changes were made to take advantage of advances in high speed digital technology. In addition to the 1 Gbps PQM modulator and demodulator, the capability was included for both 500 Mbps PDBM and PPBM. An asynchronous multiplexer and demultiplexer were included to provide both synchronous and asynchronous channel capability. To exercise the full channel bandwidth capability three distinct PN data sources (1 synchrnonous and 2 asynchronous) were provided at both the transmitter and receiver. Although these would not necessarily be part of an operational package, they were included in the SFTS and subsequently the AFTS electronics for quantitative evaluation of the channel performance.

Unlike the EFM generation electronics which used discrete circuitry to implement high speed logic function, the AFTS electronics used exclusively monolithic logic circuits. The advantages of this approach were circuit timing stability (over temperature and with aging) and lower risk circuit design.

The intricate circuitry of the receiver PQM data recovery unit used in the EFM was replaced with a traveling wave demultiplexer strip line coupler for processing. This device yielded performance comparable to the discrete PQM demodulator and consistent with operational requirements with a net reduction in power and improved circuit lifetime stability. Further reductions in second order parasitic losses could yield improved performance beyond operational requirements.

The net results of the AFTS communications electronics development were space prototype circuitry with demonstrated performance that supported SFTS high data rate link margin calculations with a power consumption consistent with spaceborne allocations, using space qualifiable circuit technology.

## 3.0 TRACKING GROUND STATION

The high data rate optical receiving terminal used throughout the AFTS program experiments was the tracking ground station located at the White Sands Missile Range, New Mexico. With the objective of being functionally equivalent to a satellite borne optical receiving terminal, the ground station (GSTA) performed the functions of high data rate detection, acquisition and tracking, and optical TT&C with the high data rate transmitter. The original ground site selected during the SFTS program was the USAF Observatory at Cloudcroft, New Mexico (Figure 3.0-1). This facility included a 48" telescope controlled by an IBM 1802 computer and control console. During the first two years of contract activity, work proceeded in three areas: (a) development of sensitive, high speed, optical receivers, (b) refurbishment of the Cloudcroft Observatory Telescope, and (c) development of the high data rate terminal (known as Package B) which would interface with the Cloudcroft telescope.

**SFTS GROUND STATION – CLOUDCROFT, NEW MEXICO** 10-9135

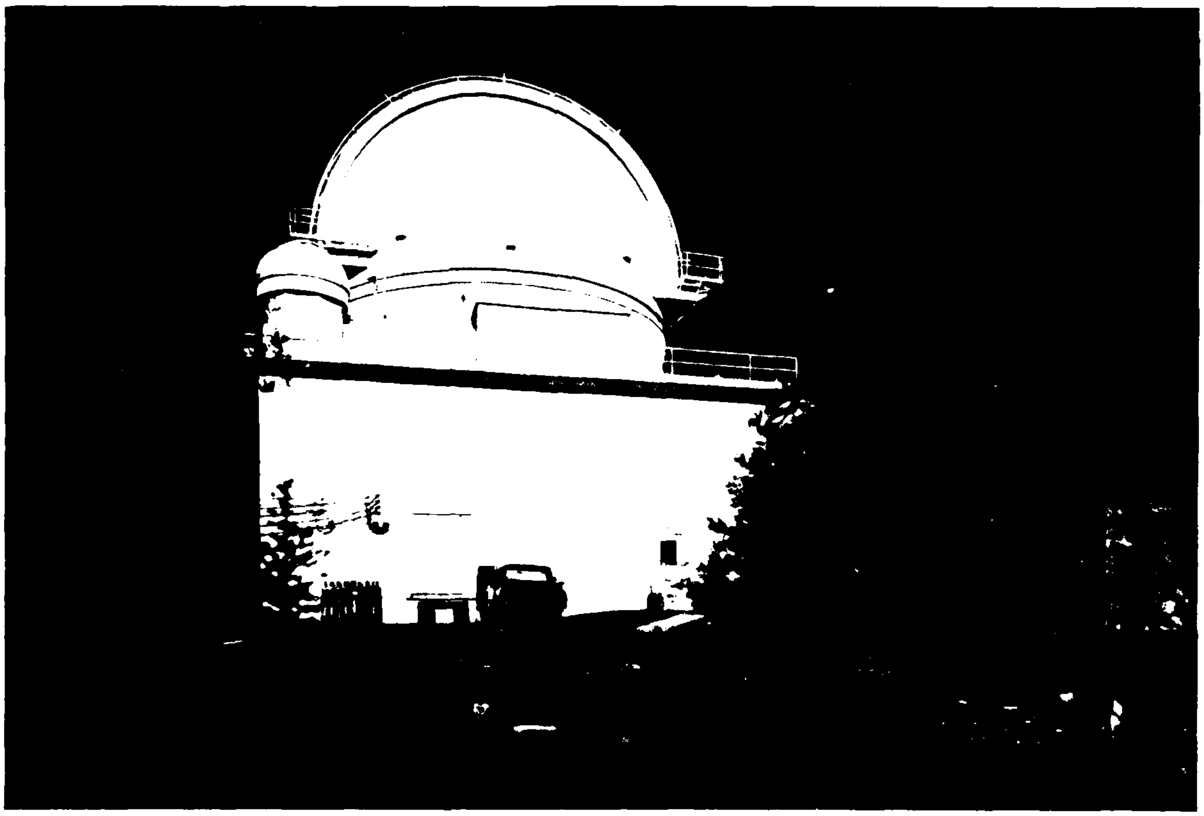


FIGURE 3.0–1

a) <u>Communications Detectors</u> - The Dynamic Crossed Field Photomultiplier (DCFP) was developed for use as a high data rate communications detector. Concurrently, the Static Crossed Field Photomultiplier (SCFP) was developed by the USAF-SAMSO for the same application. Improvements were made to both types under the preceding EFM program and the early portion of SFTS to arrive at the best configuration of each type. Considerable effort was expended to eliminate the signal induced noise dominating SCFP performance. Finally, work was stopped on the SCFP in favor of the DCFP which was then redesigned into a new rugged configuration incorporating a number of innovative improvements (Figure 3.0-2).

10-9134

**DYNAMIC CROSS FIELD PHOTOMULTIPLIER**


FIGURE 3.0–2

b) <u>Telescope Refurbishment</u> - When the Cloudcroft facility was made part of the SFTS system in 1975, several problems existed with that facility which would

have severely limited its use for an optical communications receiver. The most serious problem was a hysteresis error in the cross-track axis. In addition there was an intermittant in the track axis tachometer, and the primary and secondary telescope mirror aluminum coatings were severely degraded.

The telescope was completely disassembled and motors and tachometers refurbished. The main bearings were severely Brinelled and were reground and outfitted with oversized balls to correct for free play in the axes. To determine the proper coatings that would eventually be required for the actual SFTS experiments, it was decided jointly by MDAC and USAF to replace the aluminum coating on both with a silver reflective coating. The mirrors were coated with a Chromium undercoat, a silver reflectance coat, and a Magnesium Flouride protective overcoat. After several months, a degradation was noted in telescope transmission. This was found to be the result of deterioration in the silver coating caused by insufficient $MgF_2$ protective overcoat thickness, and poor adhesion due to poor uniformity of the Chromium undercoat. However, even with this degradation the reflectivity of the primary mirror was still greater than with a new aluminum coating, and a great deal was learned about the coating requirements for this telescope so that a successful recoat could be made prior to SFTS experiments.

c) Package B Design - During the early phase of the SFTS/AFTS program, work began on the design of the Electro-Optical receiver subassembly. Although intended primarily for the SFTS experiment, it was to serve as a brassboard development for a spaceborne receiver package. This system consisted of the High Data Rate Receiver Optical Subassembly (HDRROS), the 1.064 μm Q-switched beacon laser and associated optics, an acquisition and tracking assembly, and the interface optics required to interface the Package B to the Cloudcroft Telescope (or gimballed telescope for the spaceborne package). This design became the Brassboard Receiver Terminal (BRT) when the program was rescoped. The initial design work on the optics, and the acquisition and tracking detector was preserved and used as the starting point for BRT development. Unlike the flight equipment which had already undergone several generations of hardware development (brassboard system, EFM, and finally SFTS/AFTS), this was the first implementation of a complete receiver terminal with acquisition and tracking, high data rate receiver, beacon laser, and beacon uplink communications.

When the program scope was changed in 1977, the GSTA objectives were modified to include: (1) development of the BRT, (2) end-to-end field evaluation of the receiver concept, (3) end-to-end ground certification of final configuration for the final flight tests, and (4) complete air-to-ground system evaluation. Initially this last objective was to use a prototype receiver terminal. However, as operational users began to be developed, the utility of such a terminal became questionable and the goal of a prototype terminal was dropped, in favor of further refinement of the BRT including the addition of gimballed mirror.

With the change from a spaceborne experiment to an aircraft experiment, the Cloudcroft facility became unsuitable for a receiver terminal due to the excessive cost of maintaining the facility and the inherent difficulties associated with conducting the flight tests. The Cowan site was selected as the new Lasercom ground test facility (Figure 3.0-3). Located several miles from the Cloudcroft facility in the floor of the Tularosa Basin on the White Sands Missile Range, it had an existing steerable dome which offered the possibility of serving as both the ground test facility as well as the receiver terminal for air-to-ground operations.

**LASERCOM GROUND STATION**

10-8909


FIGURE 3.0–3

Showing a great deal of foresight on the part of USAF and MDAC, the facility still has residual utility as the optical ground station for the LSMU (Lasercom Space Measurement Unit) experiment to fly aboard the P80-1 satellite later this decade.

### 3.1 Brassboard Receiver Terminal Development

The significant achievements of the BRT development which advanced the Lasercom state of the art were that (1) the receiver acquisition and tracking system was implemented and evaluated, (2) acquisition, tracking, and communications (1 Gbps reception) were united in a single terminal, (3) 20 kbps Beacom Communications was implemented and evaluated, and (4) 100 bps call-up communications was demonstrated. These four major achievements will form the basis for the design and manufacture of future Lasercom systems.

#### 3.1.1 BRT Functional Description

Figure 3.1-1 shows the functional schematic of the BRT. In receiving the 0.53 μm signal from the transmitter, the system employs torque motor beam steerers (TMBS) for fine pointing/tracking control of the optical path common to both transmit and receive functions. The received illumination is then reflected by a dichroic down the receive path where it is divided between the acquisition and tracking detector (ATD) and the dynamic crossfield photomultiplier (DCFP) tubes used for communications reception. The power splitter, originally fixed (for tests I and II) was solenoid actuated to provide 100% of the received light to the ATD during acquisition and switching to a 5/95 split ATD/DCFP during communications.

The transmit path starts at the 3000 pps 1.06 μm Q-switched beacon laser, through scanning TMBS's and beamwidth control lens, and into the common path by way of the dichroic element. A small amount of the beacon signal is reflected off the dichroic into the corner reflector, back through the dichroic, and into the second dichroic and the alignment detector. The alignment detector monitors the position of the transmit beam and compensates for drift by adjusting a bias signal on the scan TMBS's.

#### 3.1.2 Acquisition and Tracking

The acquisition and tracking system elements unique to the receiver include (1) image dissector tracker used as Acquisition and Tracking Detector (ATD),

(2) use of torque motor driven large-area steering mirrors (TBMS's), (3) receiver mode logic, (4) transmit/receive beam alignment mechanization, and (5) beam control actuators. These elements have been successfully implemented and evaluated in the BRT.

10-2326A

## BRASSBOARD RECEIVER TERMINAL
### FUNCTIONAL OPTICAL SCHEMATIC

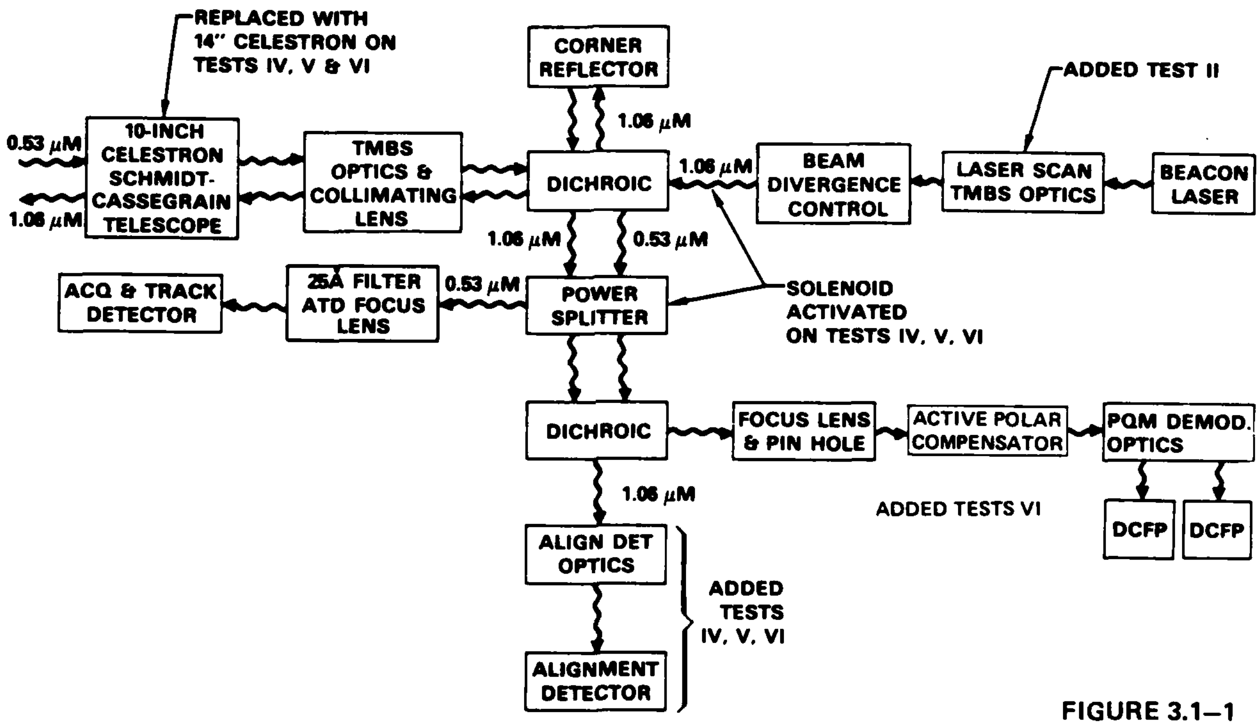



FIGURE 3.1–1

The image dissector is shown in Figure 3.1-2. This photomultiplier tube has the capability of searching 0.7 inch photocathode with a 7 mil aperture to locate a focussed spot and develop signals related to its position. In this system, the photocathode represents a ±6.5 mrad field of view and the aperture 90 μrad.

10-2319

# ACQUISITION AND TRACKING DETECTOR

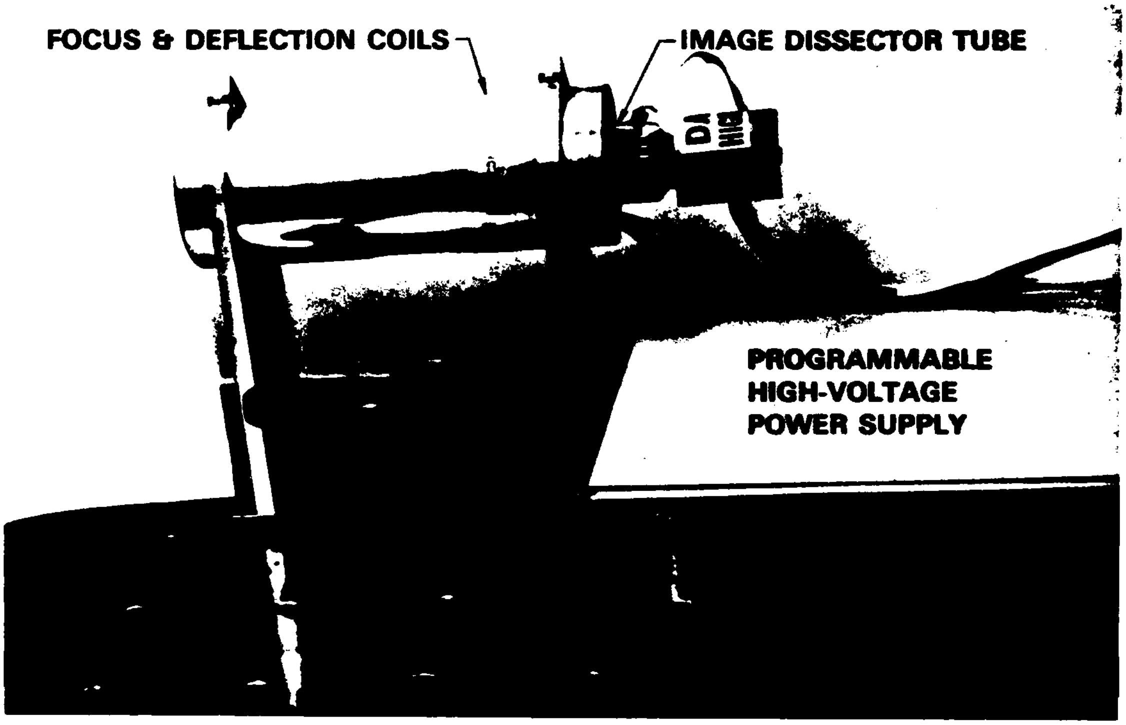



FIGURE 3.1–2

The image dissector operates in three distinct modes corresponding to the different phases of acquisition and tracking. In the coarse acquisition phase the aperture is scanned over the entire open loop pointing uncertainty area 3.9 times a second. Upon detecting an incoming signal, the image dissector scan mode is automatically switched to a tracking postage stamp scan mode and scans a narrow area corresponding to the acquisition pointing uncertainty. The frame rate is sufficient to provide angle data to support the low bandwidth acquisition loops. Finally, as the pointing uncertainties are reduced, and illumination from the transmit terminal improves, the image dissector selects the third and final scan mode; the cruciform scan. This is a very narrow 2-axis scan that supplies high resolution angle information necessary to support the high bandwidth fine tracking control loops. As with the transmit terminal there are separate requirements for the acquisition and tracking phases. The acquisition phase must have maximum sensitivity to acquire the low level illumination from the A/C, while fine tracking

requires a very low level of angle noise. Confirming link margin analysis the measured performance of the image dissector for all three operating modes was better than that required for a typical cross-link receiver terminal, with less than 3 $\mu$rad, rms of angle noise output for 10 pW of signal power in the cruciform scan mode.

Figure 3.1-3 shows two versions of the TMBS mirrors utilized in this program. The original mirror was built to accommodate a 2-foot collection aperture which was consistent with spaceborne terminal design. With commercial torque motor elements the maximum bandwidth attainable was 90 Hz, versus the original goal of 150 Hz. By reducing the area of the mirror, the inertia was reduced enabling operation out to 150 Hz control loop bandwidths. This mirror is shown on the right in the figure. Larger apertures are readily accommodated by using Beryllium mirrors for low inertia and excellent optical figure.

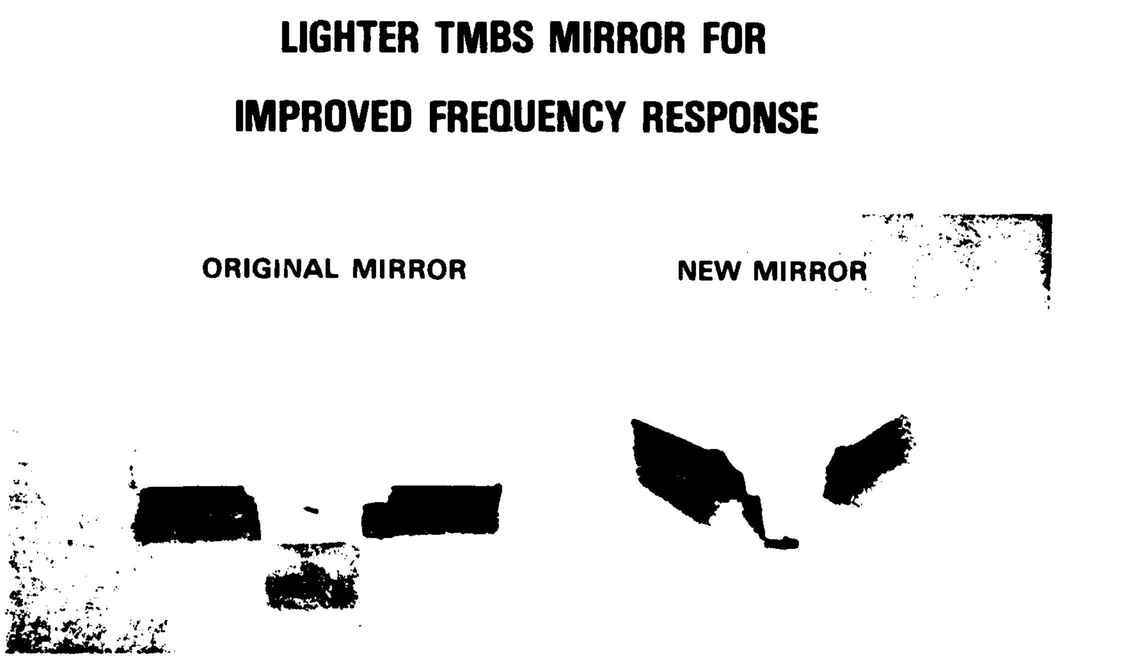



FIGURE 3.1–3

The receiver mode logic is illustrated in Figure 3.1-4. This flow diagram shows how the system flows through its various modes automatically in response to signals generated in the Acquisition and Tracking Detector (ATD). This mode logic was proven in the flight test program and closely represents the functions required of an operational receiver terminal. Certain features, such as the sun shutter and audibles, were added to protect the ATD from the sun and excessive signals which sometimes occurred during this test program.

## CONTROL MODE LOGIC

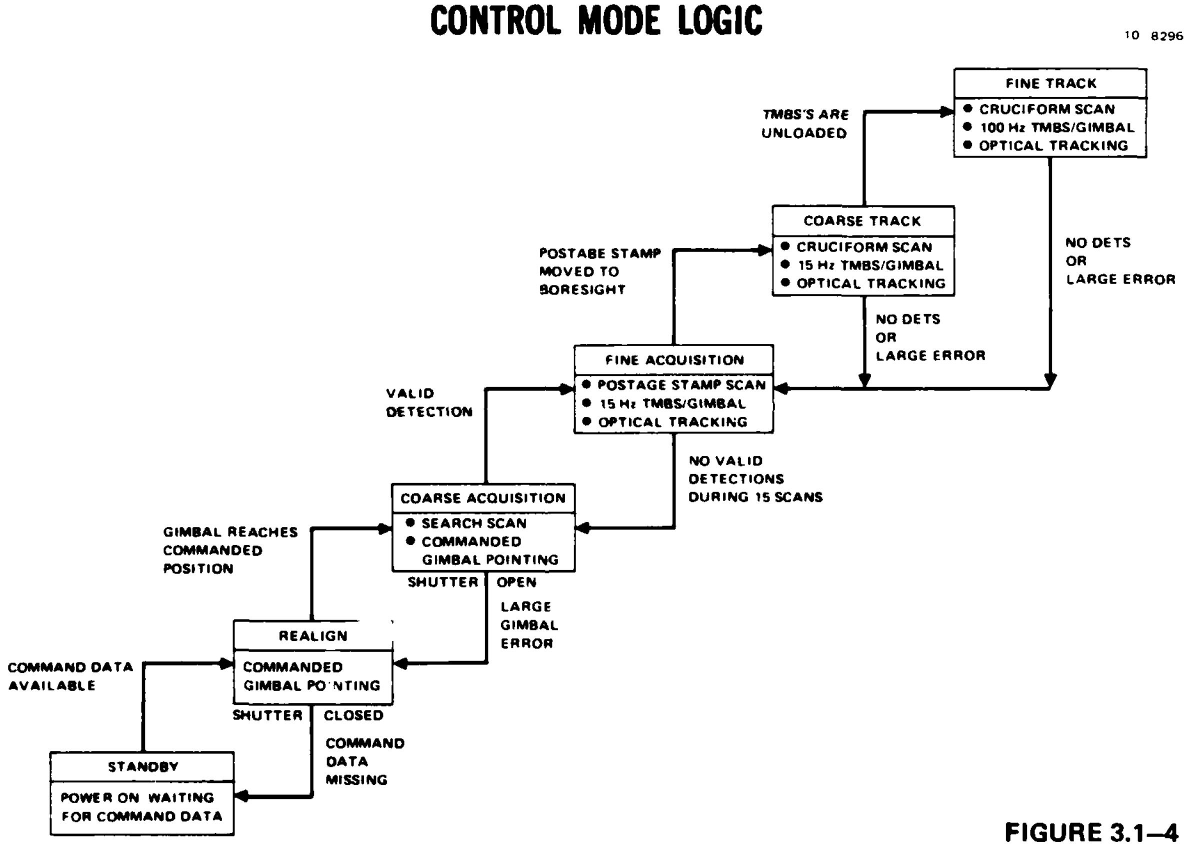



FIGURE 3.1–4

As an adjunct to the mode logic development, a discriminator in the ATD was implemented to discriminate between the 0.53 μm signal and other CW light sources such as bright stars and solar glint which otherwise would be processed in the same manner as the transmit signal. Spectral discrimination eliminates the dimmer spurious signals, but during acquisition, when the transmit beam is broadened and

is thus less bright, certain bright stars can appear as bright as the desired signal. During acquisition a 1 MHz squarewave polarization modulation is imposed on the 0.53 μm transmit acquisition beam. For Test II, circuitry was implemented in the receiver to compare the baseband energy in the ATD video signal with energy in a band about 1 MHz. Once acquisition is completed, discrimination is no longer necessary because of the relative intensity of the narrow communication beam to any potential spurious soruce. The 1 MHz squarewave modulation is replaced by data, and the modulation detection circuitry at the receiver is circumvented.

Figure 3.1-5 shows the control panel for the BRT. It was designed along with the mode logic to provide full flexibility in operating all elements of the BRT system. Each component mode is individually programmable. The BRT system modes can be selected either manually or automatically.

## BRT CONTROL PANEL

10–5106

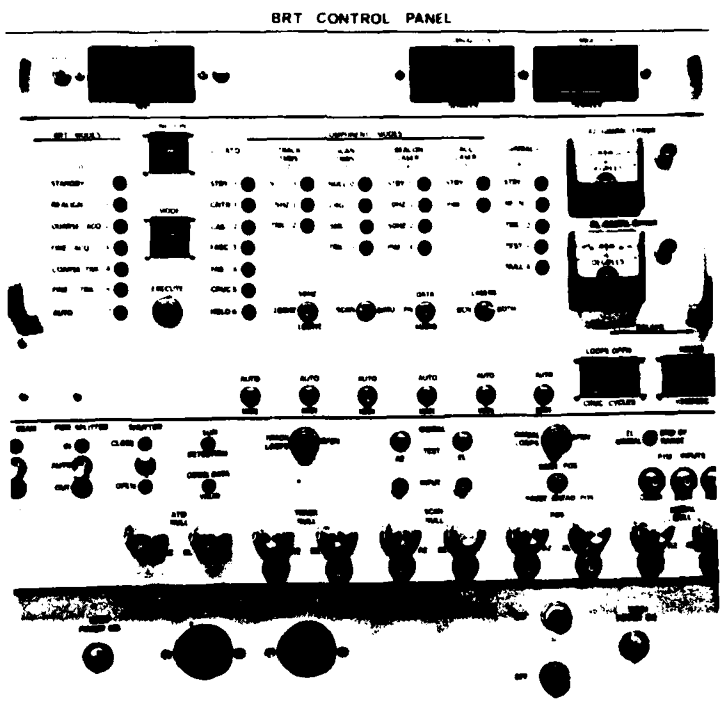



FIGURE 3.1–5

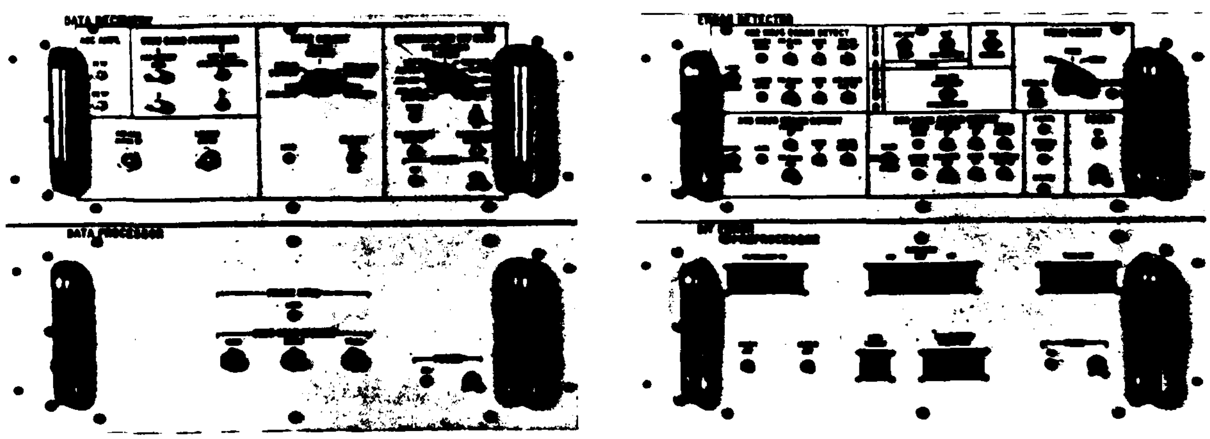
The receiver transmit/receive alignment mechanization and transmit beam control mechanization are interrelated. When the beam control mechanism was added to permit automatic switching between 1 mrad and 100 μrad beams, it was discovered that a large beam walk occurred as the result of system misalignment. An alignment detector and null-seeking loop on the scanning TMBS's was added to compensate for the walk. This arrangement reduced the walk by 90% and removed all of the dynamic drift of the scanners. The remaining 10% was compensated by a fixed bias added to the TMBS position when using the wide beam.

3.1.3 Communications Electronics

Figure 3.1-6 shows the four modules of receiver high-data-rate electronics produced during this program. These modules represent a significant advancement towards space qualification for these state-of-the-art high speed systems. In the first place, microwave techniques were utilized in the Data Recovery Unit for

**HIGH DATA RATE COMMUNICATION ELECTRONICS**

**RECEIVER ELECTRONICS**



**RECEIVER PROCESSING ELECTRONICS** **ERROR DETECTION ELECTRONICS**

FIGURE 3.1–6

improved producibility. Secondly, sensitivity to vibration and thermal effects was reduced by improving mechanical rigidity and electronic circuit stability. An operating temperature range from 40°F to 100°F was demonstrated. Thirdly, the modules were designed for hands-off operation, eliminating numerous adjustments of earlier designs and thereby achieving progress towards space design. Lastly, increased use of monolithic circuits, rather than hybrids and discretes, improved the reliability of the systems.

A provision was included in the Error Detector to count errors for each millisecond and produce a digital data stream containing these error counts and a time tag. This feature permitted the addition of a Bit Error Rate Processor (BERP) to sort out errors and correlate them with the average power level for the same millisecond time period to permit instantaneous BER visibility. Without this equipment, the BER could be correlated only with the long term average of the signal level. With the short-term signal fluctuations observed during these tests such a measure was a poor measure of actual system performance. As it was one millisecond was too long for some of the data due to higher-than-expected frequency content of the received signal scintillation. However, the analysis of system performance was much improved with the BERP and labor saving automation of the BER data gathering and reduction was a significant improvement over past techniques. Such systems will be utilized for all future BER evaluations.

Figure 3.1-7 shows a photograph of the BERP components. The control panel permitted programming of the type of errors counted and test run. The card cage contained a TI 9900 computer for sorting, storing, and processing the data. The programs were loaded by means of the small audio cassette shown in the figure. The Hazeltine 1500 CRT terminal provided operator I/O, and the Memodyne digital cassette recorder stored the sorted data for later off-line processing.

### 3.1.4 Pulse Interval Modulation (PIM) Implementation and Evaluation

During the AFTS program PIM at 20 kpbs and at 100 bps was implemented to demonstrate the technique at the two widely separated data rates which are required for the HDR communications system. Other applications at data rates different from these have since arisen, but the principles derived from the AFTS program guide the design of these new applications.

# BIT ERROR RATE PROCESSOR

FIGURE 3.1–7

Both systems utilize "differential" PIM. That is each pulse provides both the "stop" command for the previous interval and the "start" command for the succeeding interval, avoiding the necessity of clocks with long term frequency stability or loss of data capacity by periodic reference pulses. The price paid is twice the BER for the same symbol error since each slot error affects two intervals. When operating at low error rates ($10^{-6}$ to $10^{-7}$), this penalty is not significant.

The 20 kbps system utilized 128 slots of 0.5 μsec each for 7 bits per pulse and a nominal pulse rate of 3000 pps. In the laboratory, communications performance 2 dB from theoretical was achieved. In the field, the scintillating channel required that the PIM receiver in the aircraft be operated in saturation most of the time. The frequency of the scintillation on the air-to-ground was higher than the 3000-pps pulse rate so that AGC circuits were not as effective in reducing error as on the ground where the disturbances were within 1 KHz. Nonetheless, $10^{-6}$ BER was achieved and burst error statistics evaluated.

The 100 bps channel utilized a 10 bit per pulse format for the 10 pps call-up laser. This system was used for sending pre-recorded messages and was operated during flight. This capability is envisioned for verification of users authenticity when addressing a Lasercom link in a jamming environment.

3.2 Receiver Terminal Milestones

The Brassboard Receiver Terminal (BRT) development described in the preceeding paragraphs represent the most significant achievement of the ground station hardware in progress towards space deployment of the high-data-rate receiver terminal required for future strategic laser communications systems.

Figure 3.2-1 shows a schedule of the Ground Station development, listing the important milestones achieved during the 3-year time span. During that time three systems were built and operated (ground site, BRT, and gimbal). A 6-stage test program was conducted which furthered the system hardware capability at each

## GROUND STATION DEVELOPMENT MILESTONES

10 8890

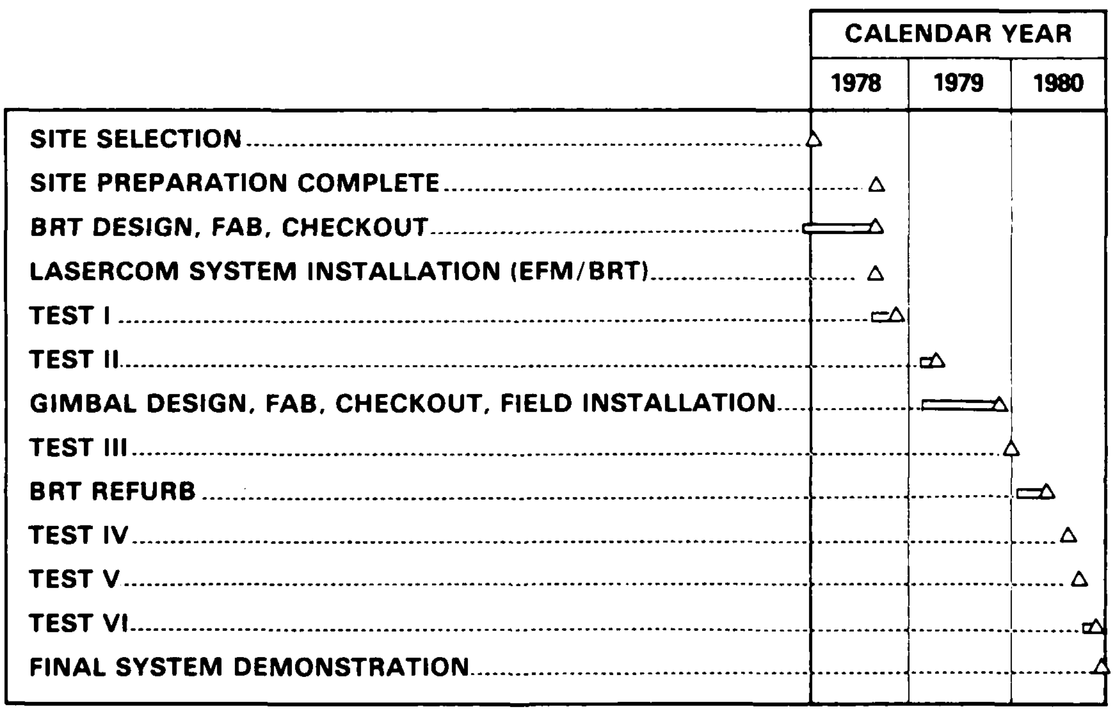



FIGURE 3.2–1

stage. The last function of each stage was to test the waters of the succeeding stage to determine if any modifications to plans, procedures, or equipment were required, thereby improving the probability of success as each milestone was approached. This practice plus the judicious use of overtime when unanticipated hurdles appeared served to keep the program on schedule and permitted the successful demonstration flights in December 1980.

### 3.2.1 Site Selection and Preparation

The USAF/MDAC team examined numerous sites at White Sands Missile Range before selecting Cowan Site for the Lasercom Ground Station. Cowan was selected because of its location and operational steerable dome. Cowan's location is about midrange, north and south, near the eastern range border. It is readily accessible by means of the Tularosa Gate, 45 minutes from Alamogordo. Many other sites considered were so far from living accommodations that travel time would have been prohibitive and on-site accommodations would have been required. Cowan site was near enough to Tularosa Gate and the eastern range border that evacuation for missile shots from launch sites to the south was not required. Also ground-to-ground laser operations did not interfere with other WSMR missions.

The steerable dome at Cowan Site mounted on its elevated pedestal provided an option for the air-to-ground site which was ultimately used, saving the considerable cost of new construction.

Prior to the initial ground-to-ground tests (I and II), the existing building was refurbished and an addition constructed. A plan view of the facility is shown in Figure 3.2-2 (with equipment arranged as for the final tests). Because of a 2-year backlog of work by the WSMR construction crews, MDAC hired an El Paso architect (Foster, Henry, Henry, and Thorpe) and construction contractor (J. R. Lavis Co.) to engineer and construct the addition and refurbishment to MDAC specifications and with the approval of WSMR engineers. These firms were selected on the basis of prior WSMR construction experience. The WSMR engineers approved of the firms as having demonstrated competence. The work was completed on schedule in August 1978, five months after letting the construction contract and eight months after site selection.

## COWAN FACILITY LAYOUT TESTS I AND II

10-5094

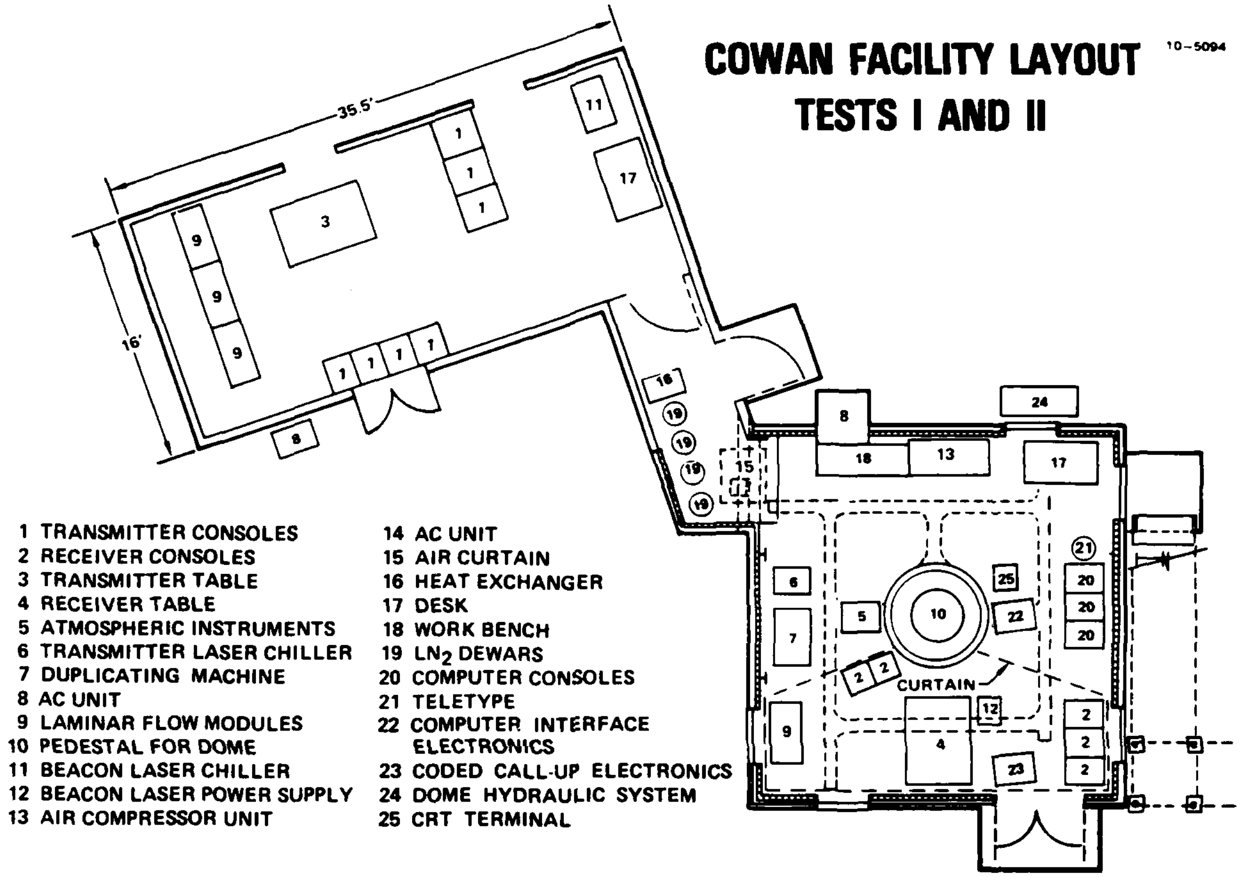


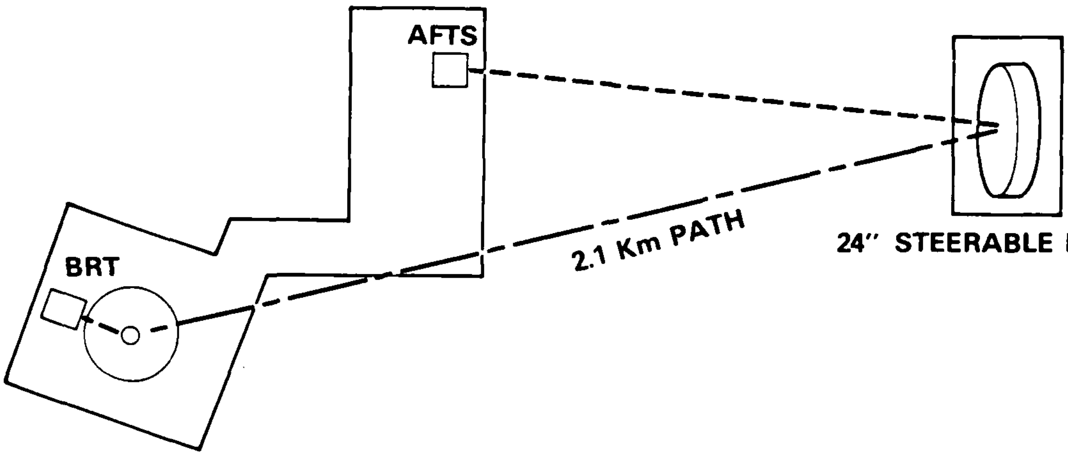

FIGURE 3.2–2

### 3.2.2 Configuration for Tests I and II

For the initial ground-to-ground tests, the EFM transmitter and BRT were operated over a 2-kilometer path from the addition to the Cowan building. In Figure 3.2-2, the transmitter was located on the optical table marked 3, and the BRT was located on another optical table in front of the other window in the addition. The laminar flow modules provided a clean room environment in the addition. The original building was used as an office area. The optical path, Figure 3.2-3, traversed one kilometer from one terminal to a 24-inch mirror, shown in place in Figure 3.2-4, then one kilometer back to the other terminal. With this configuration, both terminals could be operated by the same test team while separated optically by two kilometers.

## GROUND TEST GEOMETRY

10 5554




COWAN SITE
WHITE SANDS MISSILE RANGE

FIGURE 3.2–3

## REMOTE MIRROR AT WHITE SANDS

10-3453

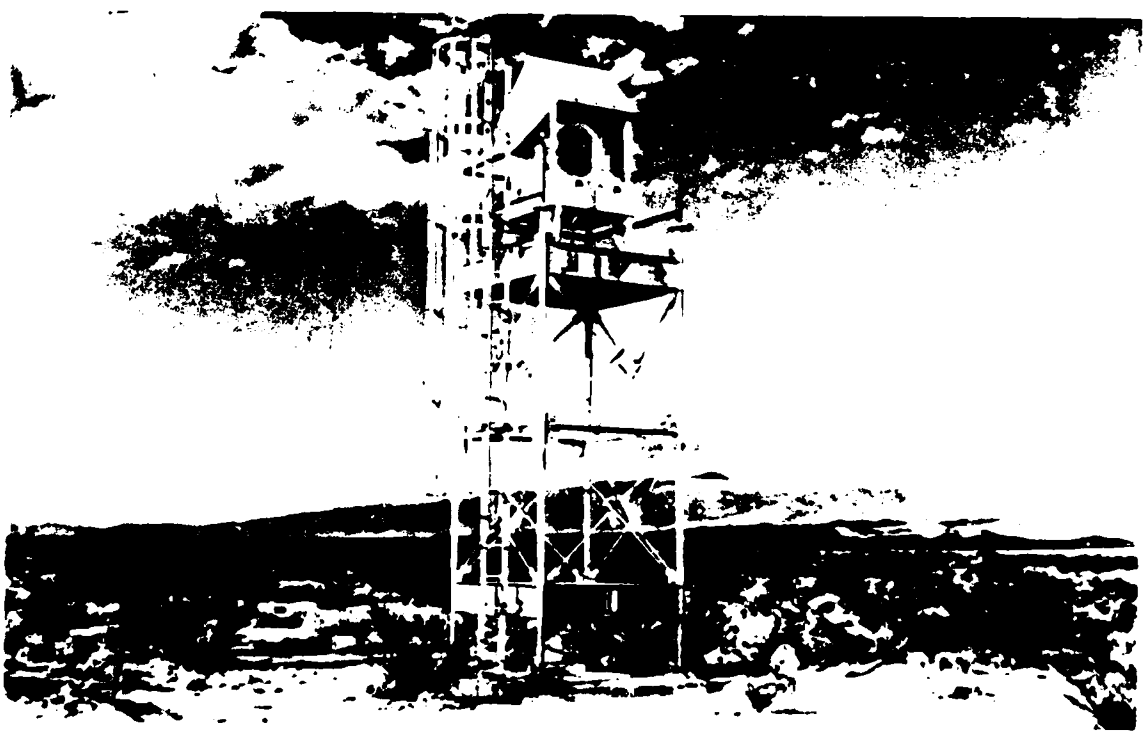


FIGURE 3.2–4

It was originally planned that Test II would utilize a 20 kilometer path by locating the remote mirror at Black Site on a mound and concrete pad located on the same line of sight as the original mirror site but 10 kilometers from Cowan Site. At the conclusion of Test I in October 1978 the mirror was transported to Black Site for a "dry run" of the planned long-range tests. The optical line of sight was established, but lock up of the link could not be maintained. After verifying that both terminals were operating correctly, measurement of the atmospheric steering of the beam was made to ascertain its magnitude and frequency. To evaluate the effects of the EFM gimbal or TMBS's control jitter, Black Site was illuminated by both the EFM green beam and a separate beam from a Helium Neon laser. Atmospheric steering of several hundred microradians was observed and noted to be well correlated between the two beams. The HeNe was then mounted in a tower at Cowan Site in an effort to avoid surface effects. Again the EFM and HeNe beams moved together. The movement is shown in Figure 3.2-5. This information, coupled with the knowledge that the angular subtense of the remote mirror, is only 61 $\mu$rad at Black Site explains why lock-up was infrequent. The atmosphere at ground level exhibits thermal gradients and numerous inversion layers which shift with the prevailing ground winds and cause steering of the beam. A convenient way to view the situation is to unfold the optical path, locating the receiver 20 kilometers from the transmitter and erecting a screen half way between containing a 2-foot diameter hole. Mutual tracking at both ends of the link tracks out angle-of-arrival fluctuations but causes a bowing or other distortion of the path to compensate for the atmospheric effects. As a result the instantaneous line of sight may or may not pass through the 2-foot hole. With the 2 kilometer path the angular subtense of the "hole" is 610 $\mu$rad. From the data in Figure 3.2-5, the beam would fall through the hole for hours at a time before adjustment of the mirror would be necessary.

As a result of the dry run at the end of Test I, Test II was conducted over the 2-kilometer path.

### 3.2.3 Configuration for Tests III through VI

Prior to Test III, the gimbal was constructed and installed in the dome at Cowan Site. The gimbal steered a beam from some point on a hemisphere down the concrete pedestal to a stationary fold mirror and into the BRT.

10 2325

# ATMOSPHERIC BEAM STEERING TEST RESULTS

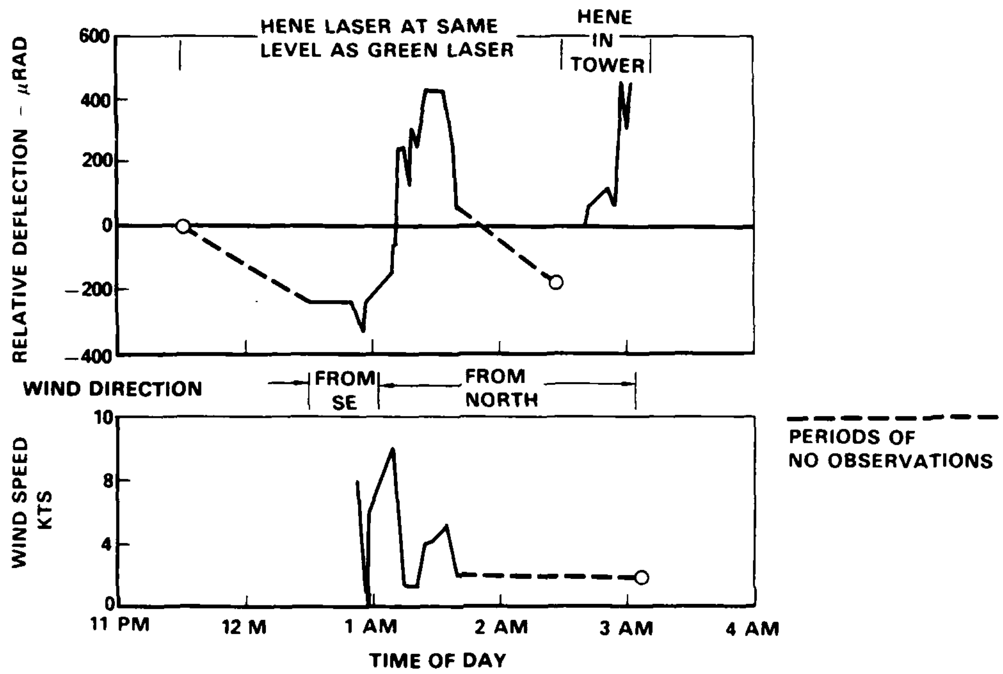



FIGURE 3.2–5

The gimbal set is shown in Figure 3.2-6. The baseplate turns about a vertical axis along the centerline of the pedestal. The azimuth mirror follows a beam along that axis horizontal into the elevation mirror along its axis of rotation. The elevation mirror folds the beam 90° to a line from the horizon to zenith depending upon its angular position. The elevation synchro, motor, and tachometer are housed in the fitting which holds the elevation mirror. The azimuth tachometer/motor assembly rotates the torque tube through which the optical path passes with a tangent drive. The azimuth synchro is mounted to a stationary "spider" assembly mounted to the support structure at the bottom of the torque tube. A similar "spider" mounted inside the bottom of the torque tube is fastened to the rotor of the synchro providing direct azimuth angle pickoff. The obscuration caused by the synchro is contained within the obscuration of the secondary mirror on the BRT telescope.

# GIMBAL SYSTEM

10 -106

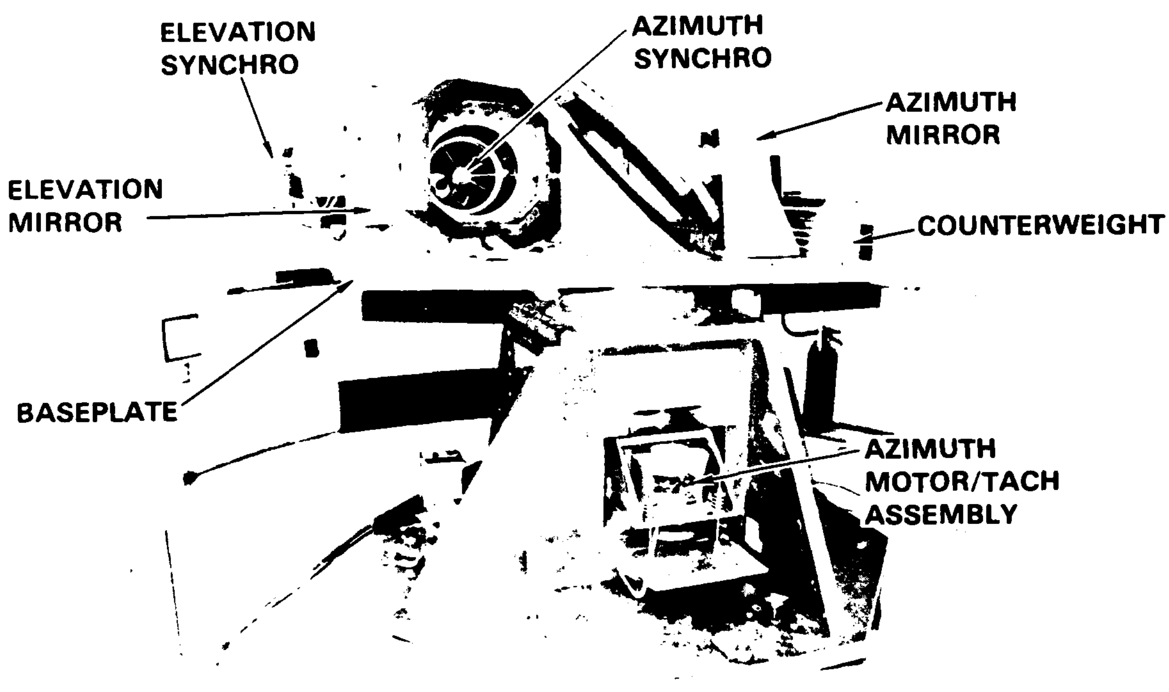



FIGURE 3.2–6

The gimbal initial pointing commands are provided by a GFE Nova 3/12 computer. The computer receives X, Y, Z radar data on the aircraft position from WSMR radar units via telephone line to a Lenkurt 261A modem. The computer calculates azimuth, elevation, and ground range to the aircraft and sends the angle commands to the BRT. The computer interface electronics, shown in the figure, interface the computer with the BRT, Lenkurt, and Chronolog Time Code Generator. A Hazeltine 1500 CRT terminal, dual floppy disk unit, and digital tape drive unit make up the computer peripherals utilized. The computer received radar data at 20 samples per second, and provided commands to the BRT 10 times per second averaging each pair of radar samples. An extrapolation algorithm was provided in the software to bridge over data outages of as long as several seconds.

### 3.2.4 Significant Hurdles Cleared

Because the test program was planned in 6 stages of hardware complexity, few problems were encountered in achieving expected system performance. Potential problems were anticipated and eliminated before they could affect field test schedules. Two significant problems which had not been anticipated occurred during the conduct of the tests. In order to maintain schedule, it was necessary to solve them in "real time" (i.e., while continuing to meet test milestones). These problems were (1) the transient boresight misalignment caused by the divergence control actuator in the BRT, and (2) the severe degradation in communications performance on the high-data-rate channel due to atmospherically induced high-frequency amplitude fluctuations.

BRT Self Alignment - The solution to the first problem was described earlier and was possible because the capability had been designed into the system but not completely implemented until the need became apparent. Operation was accomplished by (1) recoating the movable splitter to permit the 1.06 μm signal to get to the alignment detector port in all modes, (2) integrating existing detector and electronic equipment from other systems into the BRT to close the alignment loop, and (3) evaluating and modifying the system as required to achieve the desired performance.

Atmospheric Fluctuations - The frequency content of the received amplitude fluctuations were unexpected. Analysis had predicted that because of the near-ground effects of the ground-to-ground link that link would be the worst case with respect to atmospheric disturbances. Even though it was determined that the magnitude of those fluctuations was worse over the ground path, the speed at which the signal changed was an order of magnitude or more faster over the air-to-ground links. High speed (2000 frames per second) motion pictures were taken of the BRT aperture illumination. These revealed interference nulls passing through the beam at rates comparable to the speed of the aircraft.

Consequently, with the limited AGC capability there was significant signal fluctuation at the input of the bit decision circuitry in the Data Recovery Unit. Figure 3.2-7 shows a block diagram of the affected receiver circuits in one of the two polarization channels. The heavy bordered boxes were modified to reduce

effect of the signal fluctuations. The DCFP circuits were modified to increase the detector AGC bandwidth from 100 Hz to 12 KHz. This improvement was accomplished on one channel in the field, then cleaned up and duplicated on the other channel in St. Louis during the break in testing in late October and early November 1980. The Motorola AGC preamps were modified in the field to increase their control bandwidth from 1 KHz to 8 KHz. The addition of the improved threshold detector was possible because of an in-house processing improvement program already underway. The resulting electronics are shown in Figure 3.2-8. Their primary purpose was to eliminate undesired pulses from the stripline coupler which caused some degradation due to intersymbol influence. The significant by-product for the present problem was that the new circuitry was less sensitive to received signal amplitude fluctuations so that residual variations which leaked through the improved AGC system had less effect on bit error rate than would have otherwise been observed.

## RECEIVER AGC CIRCUITS

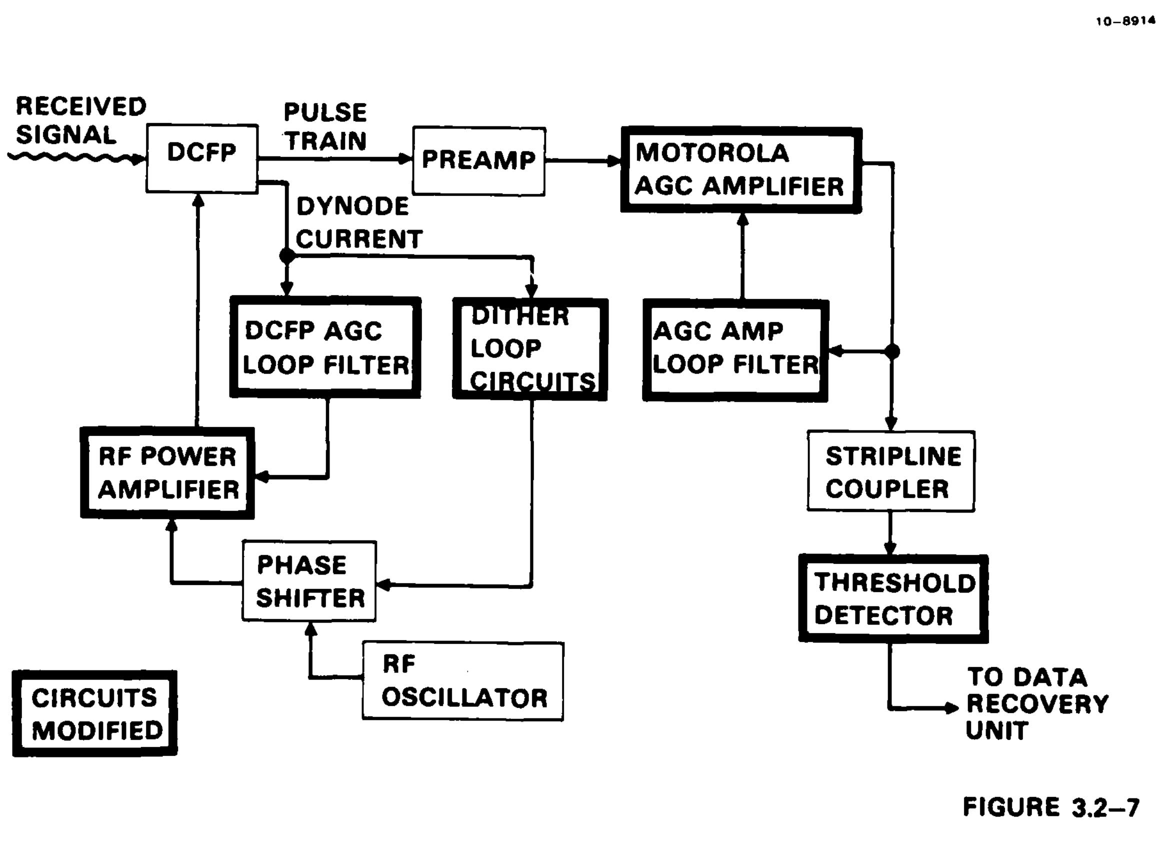



FIGURE 3.2-7

# 1 GB/S DATA DEMOD/DETECTOR

10-8946

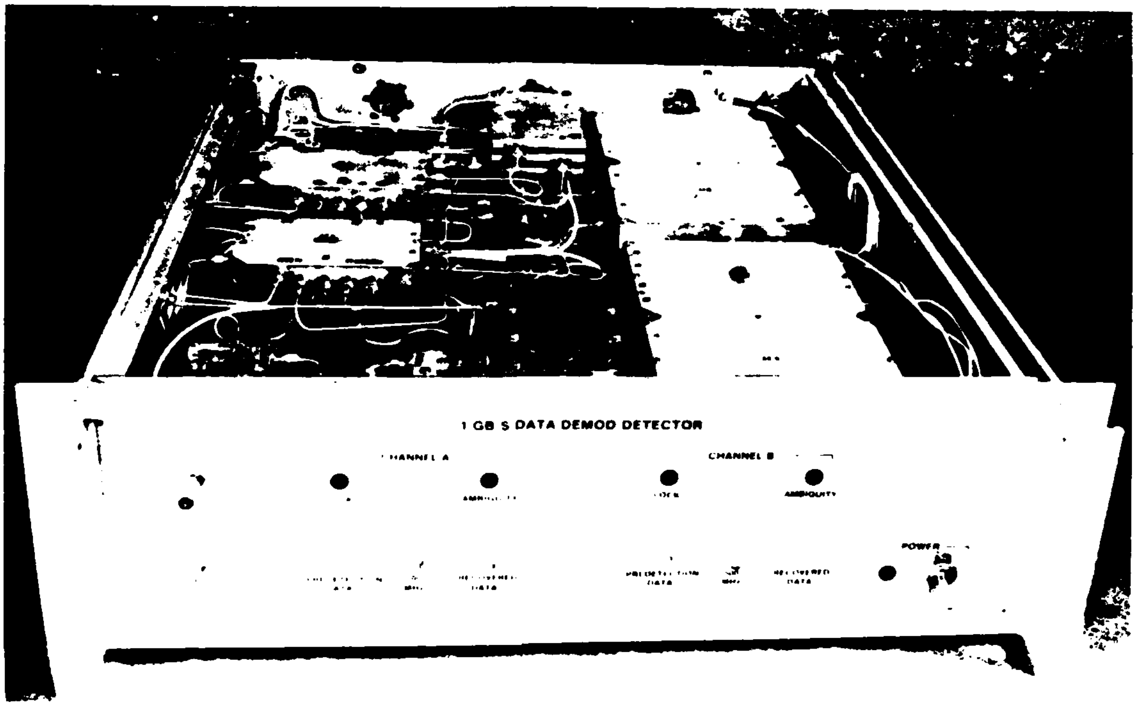



FIGURE 3.2-8

It should be noted that the high frequency scintillation was an artifact of the air-to-ground testing. All of the operational systems identified operate to a geostationary satellite from earth, from satellite to satellite, or from a high altitude aircraft to satellite. The high frequency dynamics resulting from the rapid line of sight motion through the atmosphere will have no effect on these operational systems.

3.2.5 Carry-Over to Future Programs

The Ground Station program leaves a legacy which goes beyond its contribution to the successful system tests and demonstrations. The many developments lay the ground work for future laser communications system designs.

The imaging optics configuration which evolved in the BRT forms the basis for high data rate receiver terminals now on the drawing board. The BRT acquisition and tracking system will in large measure carry over with the exception that a solid state detector will be sought to replace the image dissector tube used for the ATD.

Much of the Ground Station hardware will serve a major function on the Lasercom Space Measurement Unit (LSMU) program: the ground station buildings, the gimballed mirror set, the BRT optics, and the beacon and call-up transmitters.

Lastly, the development of automated bit-error-rate measurement capability by means of the BERP represents an improvement in efficiency of system evaluation which will serve future programs well.

## 4.0 AFTS TEST PROGRAM

The AFTS Field Test sequence consisted of six separate field tests conducted between September 1978 and December 1980 (Figure 4.0-1). The purpose of six tests was to exercise the system in the field environment at various stages of the hardware design and development to insure system compatibility with the experiment environment and provide a high degree of confidence in the success of formal flight experiments. The tests consisted of both static ground tests conducted over a 2.1 km folded horizontal path and air to ground tests which were conducted with an airborne transmitter orbiting a tracking ground station. The tests coincided with a paced evolution of laser communications equipment starting with the Engineering Feasibility Model (EFM) and Breadboard Receiver Terminal (BRT) in static ground tests through to the full airborne high data rate transmitter and tracking breadboard ground station (Figure 4.0-2). Through this series of tests the field compatibility of Lasercom design concepts has been demonstrated (Figure 4.0-3). In addition, the performance data gathered throughout the various tests has been of significant value in reducing the design risk of subsequent operational laser communications systems.

**AIRBORNE FLIGHT TEST SYSTEM TEST SCHEDULE**

10 8404

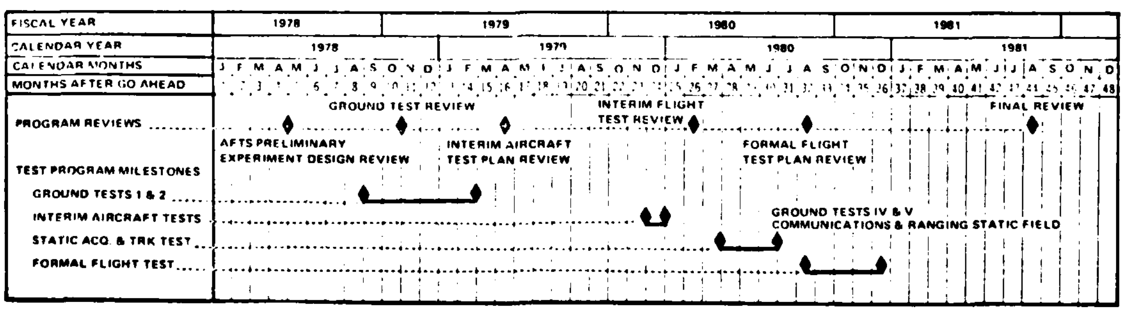



**FIGURE 4.0–1**

## 4.1 FIELD TEST I

### 4.1.1 Test Objectives

This first test was designed to demonstrate the performance of a 1 Gbps laser communications system operating over an atmospheric path and provide a stepping stone

to future tests by proving field test procedures and equipment. Specifically, the objectives were:

a. To operate the Engineering Feasibility Model (EFM) high data rate transmitter system through all modes over a 2100-meter path;

b. To observe the effects of the atmosphere on system performance;

c. To verify ⁺ e Cowan Site operating procedures and peculiarities in anticipation of future testing;

d. To operate the system over a 20-kilometer path in order to determine what prearrangements are necessary for the second tests in the series (Test II).

10-8403

## AFTS TEST HARDWARE EVOLUTION

| TEST CATEGORY | TEST | HDR TRANSMITTER | | | | HDR RECEIVER | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | EFM TRANSMITTER | A/C TRANSMITTER NO COMM. ELECT. | A/C TRANSMITTER | COMPLETE A/C PAYLOAD | BREADBOARD RECEIVER TERMINAL WITH TRANSMITTER TRACKING | BREADBOARD RCVR TERMINAL WITH TRACK. BEACON COMM SCANNING, RANGING | BRASSBOARD RCVR TERMINAL WITH ACQ LASER WITH MUTUAL TRACKING GIMBALS NO MODE LOGIC, NO HORROS | BRASSBOARD RCVR TERMINAL FULL ACQ MODE LOGIC NO HORROS | FINAL TRACKING GND. STAT |
| GROUND TEST | EFM FIELD TEST 1 | ● | | | | ● | | | | |
| | TRANSMITTER & RECEIVER FIELD TEST 2 | ● | | | | | ● | | | |
| INTERIM FLIGHT (& ASSOCIATED GND TEST) | ACQUISITION HANDOVER INTERIM FLIGHT TEST 3 | | ● | | | | | ● | | |
| | STATIC A&T FIELD TEST 4 | | ● | | | | | | ● | |
| | COMM & RANGING STATIC FIELD TEST 5 | | | ● | | | | | | ● |
| FORMAL FLIGHT TEST | FORMAL FLIGHT TEST 6 | | | | ● | | | | | ● |

FIGURE 4.0–2

# AFTS TEST SUMMARY

10 4947

| TEST | EQUIPMENT USED | | OBJECTIVE | RESULT |
|---|---|---|---|---|
| | TRANSMITTER | RECEIVER | | |
| FIELD TEST I, II<br>INITIAL GROUND-GROUND TESTS | ENGINEERING FEASIBILITY MODEL TRANSMITTER | BRASSBOARD RECEIVER | VERIFY FUNCTIONAL PERFORMANCE OF LASER COMMUNICATION IN THE ATMOSPHERE | • FIRST DEMONSTRATION OF 1 Gbps PQM TRANSMITTER OVER ATMOSPHERIC LINK<br>• ACQUISITION AND TRACKING CONSISTENT WITH LABORATORY ANALYSIS. ATMOSPHERIC SCINTILLATION RESULTED IN INCREASED DYNAMIC RANGE IN AFTS.<br>• AFTS MODULATION FORMATS COMPATIBLE WITH ATMOSPHERIC LINKS |
| FIELD TEST III<br>INTERIM FLIGHT TEST | AFTS TRANSMITTER<br>100 bps COMMAND | UPGRADED BRASSBOARD RECEIVER, GIMBAL MIRROR ASSEMBLY | FLIGHT HARDWARE ACQUISITION OF GSTA BEACON, 100 bps COMMUNICATION | • ACQUISITION OF GROUND STATION ACCOMPLISHED IN > 7.0 SEC.<br>• PROLONGED PERIOD OF TRACKING AT BOTH ENDS OF LINK<br>• ERROR FREE 100 bps COMMUNICATION |
| FIELD TEST IV<br>STATIC ACQUISITION AND TRACKING | AFTS TRANSMITTER, COMMUNICATION HARDWARE NOT NEEDED | BRASSBOARD RECEIVER WITH AUTOMATIC ACQUISITION AND TRACKING SEQUENCING | VERIFY ACQUISITION AND TRACKING PERFORMANCE OF TEST VI HARDWARE | • COMPLETE END-TO-END AUTOMATIC MODE LOGIC SEQUENCING VERIFIED |
| FIELD TEST V<br>STATIC COMMUNICATION TESTS | AFTS TRANSMITTER 20 Kbps COM. 1 Gbps COM. | FULL TRACKING GROUND STATION, ALL COMMUNICATION EQUIPMENT | VERIFY COMMUNICATIONS PERFORMANCE OF TEST VI HARDWARE | • 20 Kbps PIM VERIFIED, HIGH QUALITY VOICE TRANSMITTED OVER LINK<br>• 1 Gbps COMMUNICATION VERIFIED IN FIELD OPERATIONS |
| FIELD TEST VI | AFTS TRANSMITTER | FULL TRACKING GROUND STATION | DEMONSTRATE COMPLETE ACQUISITION AND COMMUNICATION OVER AIR-GND LINK | • SUCCESSFUL DEMONSTRATION OF LASER COMMUNICATIONS |

FIGURE 4.0–3

### 4.1.2 Results and Conclusions

The system was installed and operated successfully over the 2100-meter path. Tests were performed in accordance with the test plan (CDRL Item 020A3), on the acquisition and tracking system, the communications system, and the far field pattern of the EFM transmit beams. In addition the system was briefly operated over a 20-kilometer path.

Acquisition and Tracking Tests

These tests included measurement of the sensitivity of the EFM acquisition and tracking detectors and of the performance of the system in terms of acquisition and tracking error.

The major results are summarized in Table 4.1-1 which shows the system performed quite well during the tests, with acquisition times less than 2 seconds and tracking error as low as 3 μrad including atmospheric effects. The EFM is constructed to produce a focused spot on its detectors for a point-source transmitter at infinity. In ground-to-ground test configuration the transmitter was neither a point source nor at infinity. As a result, the defocussed images on the detectors represent larger angular spot sizes than in the laboratory where a collimated beam illuminated the EFM aperture. If the data is scaled to account for the increased spot size due to the test geometry, the results are comparable to laboratory data.

TABLE 4.1-1
FIELD TEST I
ACQUISITION AND TRACKING DATA

| TEST | RESULTS | REMARKS |
|---|---|---|
| Acquisition Time Time | >1.7 Seconds | -Based on 100 Acquisitions |
| Coarse Acquisition Pointing | 90 μrad to 150 μrad Peak error (Near Field) | -30 μrad to 50 μrad far field<br>-Test run Afternoon, Evening, Night |
| Fine Track Pointing | 3 μrad to 21 μrad Peak Error (Near Field) | -Static Tracking Performance Dependent on Atmospheric<br>-0.4 μrad to 3 μrad in Far Field |

Communications Tests

The communications system also performed at near-laboratory levels over the test range. The system was operated over the 2.1 km path using the various modulation formats and power levels and bit error rate measured. At night the system performed very well in spite of atmospheric scintillation at times having a noticeable effect on requried power. During the day, amplitude scintillation caused excessive errors the few times data was taken. Based on the performance of the communications equipment decision was made to conduct further measurements during Test II to increase the statistical sample of communications data.

Far-Field Pattern Tests

The far-field patterns of the EFM transmit beams were measured three ways: (1) inside the laboratory by photographing the receiver image when receiving the EFM output, (2) over the range by photographing the beam on an observation screen after it had traversed 2100 meters through the atmosphere, and (3) over the range by steering the EFM gimbal and measuring the average received power through a 1-inch aperture at the receiver. This measurement was difficult to make repeatably, but the results were generally consistent. The decentered pupil beam and the spoiled beam were larger than intended due to, presumably, some misadjustment occurring between St. Louis tests and WSMR tests. The collimated beam was spread to 56 $\mu$rad by the atmosphere over the 2100-meter path.

Long Range Trial Run

In an attempt to operate over the 20-kilometer path to Black Site it was found that the 67 $\mu$rad aperture formed by the 24-inch mirror at 10 kilometers truncated the beam, making the atmospheric beam steering intolerable. Since this configuration was artificial, the decision was made to operate at the short-range for all remaining ground-to-ground tests.

## 4.2 Field Test II

During the period from 1 January 1979 through 15 April 1979, the laser communications equipment at Cowan Site was utilized to perform the sequence of tests described in General Test Plan for Field Test II. In addition, certain tests of opportunity were performed to certify new hardware designs using the field test setup as a test bed. A simulated air to ground test sequence was performed to gain insight into the effects of the operational constraints on air-to-ground tests.

### 4.2.1 Test Objectives

The primary objective of this second series of tests (Test II) was to evaluate the acquisition and tracking characteristics of the High Data Rate receiver by itself and of the system as a whole (transmitter and receiver working together). Specifically, the objectives were:

a. To evaluate the far-field acquisition and tracking performance of the Breadboard Receiver Terminal (BRT) and Engineering Feasibility Model (EFM) working together.

b. To evaluate both high data rate (HDR) and beacon communication systems, the former being additional data to augment Test I results and the latter being the first time the Pulse Interval Modulated (PIM) beacon link had been exercised over the 2.1-Kilometer path.

c. To evaluate two-way ranging using the beacon and HDR communications links.

d. To evaluate, in conjunction with the HDR communications test, high speed avalanche photodiodes (APD's) as possible replacements for the dynamic cross-field photomultiplier (DCFP) tubes and new HDR electronics from Motorola using stripline data recovery techniques.

### 4.2.2 Major Results and Conclusions

The tests were performed as described in the General Test Plan, Field Test 2 (CDRL Item 020A3) plus additional tests on high-speed avalanche photodiodes and the Motorola stripline coupler for the HDR communication receiver electronics. All tests were performed over the 2100-meter path as recommended in the Test I report.

Acquisition and Tracking Tests

These tests included evaluation of the BRT far-field coverage characteristics, acquisition time measurement, and tracking accuracy as well as performance of the EFM and BRT mutually tracking. The far-field pattern measurements indicated a beamwidth slightly larger than the 1 mrad design value and adequate far-field coverage during the acquisition mode. The coverage was determined by observing the pulse rate at a number of points in the acquisition field. In all cases the number of pulses was greater than the design value indicating adequate overlap built into the beam configuration for a successful air/ground test.

The acquisition time tests indicated that the receiver acquisition logic contributed an average of 0.5 second to the total acquisition process from the time light is received in the acquisition field to the time the fine tracking mode is entered. This time was measured with initial off-axis positions around the edge of the field on the 8 points of the compass plus a ninth location on axis.

Peak coarse tracking errors from 5 μrad to 15 μrad were observed. These results were consistent with pointing a 100 μrad operational communication beam. In coop-

erative fine tracking, both the EFM and BRT performed as expected with the test geometry making the spot sizes and tracking accuracies somewhat greater than those postulated for operational concepts (as in Test I). Variations in tracking values are attributed to variations in atmospheric beam perturbations. The EFM error ranges from 2.2 μrad to 11.6 μrad peak and the BRT from 4.7 μrad to 11 μrad.

Communications Tests

The 20 Kbps beacon communications link was successfully field tested for the first time. Additional signal margin of 10.5 dB was required in order to accommodate the atmospherically induced fluctuations. System design allowed for 16 dB of degradation including 6 dB for atmospheric transmission loss. The lowest error rate achieved was 3 x $10^{-7}$ somewhat better than our $10^{-6}$ design point. Data at these low error rates was difficult to obtain due to long experiment periods required for a statistional sample. For the 20 kbps link a bit error probability of 0.3 parts per million is an error rate of one every 2.75 minutes. At this rate over 4.5 hours would have been required to accumulate a statistically significant 100 errors. Constancy of test conditions over this period of time was impossible. Slight disturbance in the tracking system at either end dominated the error results.

The atmospheric disturbances shed a new light on the relationship between required power for tracking and that for PIM communications. For fast outages, the tracking system operating in a bandwidth of 300 Hertz maximum, did not react. However, the communication system made errors instantaneously. Therefore, in the presence of rapid fluctuations the tracking system performance could be inferred from the average signal level whereas the communications performance was related to the minimum signal. Even so, designs for space application accommodated these relationships such that tracking, rather than 20 kbps BER constrained required signal strengths.

The HDR communications tests were also successful. The system operated at $10^{-6}$ BER. Although demonstrated in the laboratory to be of comparable sensitivity to the DCFP, the APD's without adequate AGC were found to be somewhat inferior to the DCFP's in field testing. This was due to the strong scintillations present in the near ground horizontal link. Therefore, the DCFP was retained as the baseline

detector for the air-to-ground tests. However, a significant body of knowledge was obtained about the use of APD's in this application. The APD's were found to be fully adequate for operational use.

The performance of the new Motorola stripline coupler electronics was equivalent to the performance of the EFM electronics.

Air/Ground Test Dry Run

A simulated air-to-ground test sequence of an acquisition handover experiment was successfully performed. The two terminals were physically isolated as much as possible and communications between the two limited to a two-way voice circuit. The results emphasized the value of such rehearsals in ironing out procedural problems prior to flight testing.

Ranging Test

Static ranging was conducted between the receiver and transmitter over the horizontal path. The test was conducted using breadboard equipment in both the EFM high data rate communications electronics and the BRT beacon communications electronics. The objective was to determine the roundtrip transit time between the two terminals. Ranging was accomplished by marking the time of transmit of each beacon pulse at the BRT. The pulse was received at the EFM tracking detector and time of detection plus turnaround delay was returned over the high data rate link. The BRT communications electronics stripped this timing information from the formated data stream and used this information in conjunction with time of transmit information to determine range and range rate. Significant effort was expended in developing accurate threshold circuitry at the EFM and high speed counters at the BRT. The system was operated in the field; however, with marginal success due to unstable operation of the high speed counting logic. This problem was determined to be the result of limitations in the specific breadboard counting circuits. With the principles of accurate laser ranging having been reduced to practice in numerous operational systems, the USAF SPO reviewed the requirement to demonstrate ranging in the AFTS experiment. Because it was felt that the design of the AFTS system was capable of achieving the required 10' accuracy, and that laser ranging was currently a practiced state of the art, the SPO determined that a greater emphasis should be expended on system development at the expense of further pursuing development of laser ranging.

## 4.3 Field Test III

The series of flight tests completed as part of the Lasercom AFTS Field Test III experiments were conducted on 10 separate missions flown in the first two weeks in December, 1979. These flights were flown on the C-135 USAF aircraft modified for the AFTS program. Flights were flown at ground ranges from 20.6 km to 56 km and at a 30 kft. nominal altitude.

The purpose of the experiments conducted on these flights was to evaluate the performance of the airborne acquisition and tracking system and obtain as much data as possible on the air-to-ground test configuration to reduce the risk on the final flight tests.

### 4.3.1 Test Objectives

In order to evaluate the AFTS acquisition and tracking system performance six separate objectives were described in the General Test Plan for Field Test III:

(1) Measure Static Boresight Stability
(2) Measure Open-loop pointing accuracy/stability
(3) Demonstrate 100 bps call-up communications
(4) Evaluate MAR handover control
(5) Measure NFD Coarse Pointing Accuracy
(6) Measure Acquisition/tracking handover time
(7) Demonstrate downlink illumination

### 4.3.2 Results and Conclusions

The Test III experiments were successful in meeting all of the above objectives. In addition, early availability of several Ground Station components allowed for two additional experiments: Cooperative acquisition/tracking handover, and extended fine tracking lockup. A summary of Test III results is shown in Table 4.3-1.

<u>Static Boresight Alignment Drift</u>

This experiment was conducted using the static boresight alignment path of the AFTS Imaging Optics. By monitoring the Point Ahead alignment correction required to maintain the alignment between transmit and receive paths, the nature of any

TABLE 4.3-1

FIELD TEST III
SUMMARY

| EXPERIMENT | OBJECTIVE | TEST III RESULTS |
|---|---|---|
| STATIC BORESIGHT ALIGNMENT DRIFT | o <5 μRAD | o <2.5 μRAD |
| 100 BPS MULTIPLE ACCESS COMMUNICATION | o VERIFY CONCEPT | o CONCEPT VERIFIED |
| OPEN LOOP POINT TO MAR | o DETECTION PROBABILITY >90% ON MAR | o MAR DETECTION PROBABILITY ~ 100% OPEN LOOP |
| | o OLP STABILITY ACCURACY BETTER THAN ±2.2° | o STABILITY AND ACCURACY BETTER THAN 1.1° |
| MAR TO WFD HANDOVER | o WFD DETECTION PROBABILITY >90% WITH MAR LOOPS CLOSED | o >92% WFD/NFD DETECTION PROBABILITY |
| | | o ACCURACY SUFFICIENT FOR HANDOVER TO NFD (FOV ±750 μRAD |
| NFD COARSE POINTING | o <±530 μRAD | o <±240 μRAD |
| ACQUISITION TO TRACKING HANDOVER | o RELIABLE ACQUISITION TO TRACKING HANDOVER | o OVER 95% ACQUISITION HANDOVERS PERFORMED SUCCESSFULLY WITHOUT FAILURE. |
| | o ACQUISITION TIME <30 SEC | o TYPICAL ACQUISITION TIME OF 7 SEC. |
| | o DEMONSTRATE BACKUP OPERATING MODE | o ALL POSSIBLE BACKUP MODES OPERATIONAL. |
| GSTA ILLUMINATION | o DETERMINE GSTA ILLUMINATION STATISTICS DURING ACQUISITION | o RECEIVED POWER MEASURED OUT TO 56 KM |
| | | o RECEIVED POWER MEASURED DURING TRACKING |

ADDITIONAL FIELD TEST III ACCOMPLISHMENTS

| | |
|---|---|
| TRACKING | o FINE TRACKING LOCKUP DEMONSTRATED |
| COOPERATIVE ACQUISITION HANDOVER | o "HANDS OFF" ACQUISITION HANDOVER TO TRACKING AT BOTH TERMINALS |

optical boresight drift could be determined. It was found that, although the imaging optics appeared to be stable in the operating environment, the laser itself demonstrated some boresight angular drift. Relative to the apparent motion in the far field for the 5 μrad beam, this drift was small and within the required tolerances for static boresight correction ( 2.5 μrad). However, the 1.5 mrad acquisition beam added for aircraft to ground operations to facilitate acquisition exhibited larger uncertanties. The laser boresight instability was found to have a significant impact on the alignment of this beam. As a result of these tests, recommendations were made and later implemented for changes to the laser/modulator interface optics to correct for laser drift.

Open-loop Pointing Handover

In order to initiate acquisition with the ground station, the airborne terminal had to be able to point to the ground station on the basis of aircraft location and aircraft inertial position. This pointing was required to be accurate to ±2.2° to accomplish handover of gimbal control to the MAR. The pointing commands also required the stability for handover of gimbal control from the MAR to the WFD. Results from these tests showed that the dynamic open-loop pointing errors were within the central four elements of the MAR (±1.1° Az El) 79.1% of the time. This accuracy was well with the limits of the MAR closed loop control capability for handover to the WFD.

100 BPS-Callup Communication

During the Test III experiments an ASCII character message of 316 letters was transmitted to the aircraft a number of times over the 1.064 μm callup link. From the performance of this communications link operation of an optical PIM link in the presence of a scintillating signal was verified. The capability for an error free transmission over a fading channel was verified, supporting the design approach for the beacon communications PIM equipment for Field Test VI.

MAR-To-WFD Handover

The second step in the AFTS acquisition sequence is handover of gimbal control from the MAR to the WFD. This process was demonstrated on repeated acquisitions during Test III. Based on a representative sequence this step worked with successful handover to the WFD better than 98% of acquisition attempts. In fact,

direct handover from the MAR to the NFD bypassing the WFD occurred more than 70% of the acquisition sequences.

Acquisition Coarse Pointing

The requirement of the NFD coarse pointing phase of acquisition is to point at the ground station with sufficient accuracy to provide stable illumination of the ground station receiver with the 1.5 mrad by-pass acquisition beam. This was demonstrated in two ways during the Test III experiments. The first method was to measure the NFD pointing errors using the MAR as a scoring detector. Results from analysis of this data indicated that the GSTA would be illuminated by this beam at least 70% of the time. The second method was by actually measuring the detection statistics with the 1.5 mrad beam at the ground station. Even with reduced sensitivity of the ground station acquisition detector, better than 50% average detection probability was measured at this stage of acquisition. To support acquisition handover at the GSTA with 15 Hz loops, better than 50% detection probability is required at the ground station.

Acquisition To Tracking Handover

Acquisition handover was measured for a number of cooperative acquisition sequences. The acquisition process proved very reliable for the primary (MAR/WFD/NFD/FTD) and all back-up modes with the average acquisition time on the order of 10.3 seconds.

Cooperative Extended Tracking Lock-up

With the early availability of the fine tracking system at the ground station it was possible to demonstrate extended periods of cooperative fine tracking. During these periods data was taken on the AFTS tracking bandwidth, tracking stability and the effect of the platform environment on the tracking system. A wealth of data was gathered for this experiment that impacted to Test VI operations.
(1) Both systems tracked with reasonable accuracy although neither the AFTS or GSTA track loops had been optimized, (2) Tracking performance was found to degrade with the higher bandwidths in the aircraft, (3) Baseplate isolation system resonances at 0.5 Hz and 1 Hz were noted. Several of the aircraft maneuvers (Dutch Roll) coupled into these resonances driving the track TMBS's into saturation. The results of these findings were to (1) include into the Test VI test plan provisions for characterizing the detector spot size and track loop bandwidth to

determine the source of the tracking instabilities, (2) increase the resonant frequencies of the baseplate isolation system to 1 Hz and 2 Hz in the two axes, and (3) increase the dynamic range of the tracking TMBS's from 180 μrad to 250 μrad.

## 4.4 Field Test IV

### 4.4.1 Objectives

This series of experiments was conducted to evaluate the cooperative acquisition and tracking performance of the AFTS and ground station in the static ground test configuration. As a result of the Test III experiments a number of engineering tests were planned in addition to the specific test plan experiments.

### 4.4.2 Results and Conclusions

Although a number of problems were encountered with the final series GSTA BRT modifications, Field Test IV was successful in that it provided base of data on the acquisition and tracking system that would be important in evaluating the Field Test VI data. Also, the instrumentation techniques for evaluating the tracking system performance inflight were worked out and calibrated against the standard procedures used in laboratory and ground tests. One of the most significant findings to come out of Test IV, however, was a better understanding of laser boresight motion and the relationship of laser/modulator alignment to system boresight alignment. From the results of this test further modifications were incorporated into the interface optics to provide for remote Laser/Modulator decenter alignment capability as well as tilt alignment capability. The procedure worked out for initial system alignment was found to give a repeatable boresight alignment.

## 4.5 Field Test V

### 4.5.1 Objectives

The final ground test scheduled for the AFTS program was dedicated entirely to evaluation of both the beacon and high data rate communication links. The goal was to establish performance baselines that would be used in evaluating the Field Test VI data.

### 4.5.2 Results and Conclusions

The performance demonstrated for the 20 kbps beacon PIM link showed that the system was capable of transmitting low error rate data ($<10^{-6}$ probability of error) when there is sufficient signal for stable tracking. Although the fixed threshold receiver performance was predictably worse than the AGC receiver in a scintillating environment, both receivers demonstrated acceptable performance for Field Test VI operations. The ground-to-ground atmospheric performance was within the bounds of the 16 dB allotted in the link margin predictions for atmospheric effects.

The high data rate communications data taken during Test V showed that the system was performing within the expected bounds based on the results of the communications test-bed evaluation. No difficulties with full system operation or atmospheric dynamics were found during the ground test activity. The communication performance recorded over the 2.1 km path was consistent with that obtained with the EFM during Field Tests I and II.

## 4.6 Field Test VI

The final series of experiments conducted as part of the AFTS program were the Formal Flight Tests (Field Test VI) and were conducted during the time span from August 1980 to December 1980. A total of 35 separate flights were flown totaling more than 200 flight test hours. The overall objective of this series of experiments was to demonstrate the full laser communication system which includes acquisition, sustained tracking, beacon uplink communications, and the full 1 Gbps channel capacity of primary data communications. The performance of these design concepts in the air-to-ground environment provided data that would serve to reduce the risk of component development for future space and airborne applications of optical communications with Nd:YAG laser.

### 4.6.1 Objectives

The overall objective of Field Test VI was broken into seven specific experiments:

Acquisition Detector Sensitivity
Cooperative Acquisition Pointing
Acquisition Time
Cooperative Tracking

Boresight Alignment - Far Field Patterns
20 Kbps Beacon Communications
High Data Rate Communications

These experiments were to demonstrate the various aspects of laser communications system operation over ground ranges from 11 km to 100 km.

4.6.2 Demonstrated Design Concepts

The AFTS Lasercom system incorporated the same concepts for acquisition, tracking, and uplink and downlink communications as spaceborne system concepts. Results from the Field Test VI experiments successfully demonstrated key aspects of (1) acquisition handover, (2) accurate sustained cooperative tracking, (3) low bit-error rate beacon communications, and (4) low bit error rate 1 Gbps high data rate communications.

Acquisition Handover

The concept of acquisition handover is the automatic cooperative acquisition of both beacon and HDR laser links starting from initial platform attitude and position (ephemeris) data.

In the AFTS system the demonstrated capability was to reduce initial uncertanties on the order of 2° to tracking handover. The design goal was to achieve this acquisition in less than 30 seconds. AFTS results for the primary acquisition mode were an average time 8.5 seconds and a maximum time of 14.4 seconds. Starting from the typical satellite uncertainty of ±0.2°, an average acquisition time of 5.2 seconds was demonstrated. The design goal for the SFTS platform was a mean acquisition time of 6.0 seconds from this uncertainty field. Thus, the SFTS design goal was achieved with the adverse platform dynamics of the airborne platform. The acquisition handover was demonstrated to be nearly 100% reliable.

Stable Tracking

To communicate with the narrow beams (5 μrad to 100 μrad) inherent with laser communications, it is necessary for the two terminals to maintain precise optical tracking. The budgeted tracking performance for the AFTS was 35 μrad. This was required to support communications with a 100 μrad transmit beam. Anticipated

residual errors from aircraft platform dynamics (rigid and non rigid body motion) were expected to be on the order of 5 μrad with the remainder of the budget left for the atmospheric anomalies peculiar to the air-to-ground slant path geometry. Demonstrated performance with the AFTS system were total residual tracking errors (platform plus atmospheric) on the order of 9 μrad to 12 μrad. Platform dynamics were estimated to be an insignificant portion of the total tracking errors. It is expected that in the absence of atmospheric perturbations and aircraft platform vibration, the system would have demonstrated performance equivalent to the 0.6 μrad laboratory performance. Additionally, there were periods of sustained tracking lasting up to 1 hour (generally terminated intentionally) demonstrating the capability to maintain fine track in the presence of a variety of platform dynamics, atmopsheric effects, and optical backgrounds.

### 20 Kbps Beacon Communications

The Pulse Interval Modulation (PIM) communications format is an efficient format well suited to moderate data rate transmissions with pulsed lasers. This concept was used on the AFTS Beacon Communications link. Sized to accommodate general satellite payload and housekeeping command requirements, or a typical voice link, the system was designed to transmit variable data rates from 1 bps to 20 kbps. Even in the presence of adverse atmospheric scintillation rates, an average bit error rate of $10^{-6}$ was demonstrated on the AFTS PIM link with signal levels commensurate with tracking system requirements.

### High Data Rate Communications

The high data rate communications link is the primary communications link of the AFTS system. The link was designed to transmit either PDBM or PPBM 500 Mbps formats or a PQM 1 Gbps format.

The design goal was to transmit high data rate information at ranges out to 100 km with low bit error rate. During Field Test VI near $10^{-6}$ average bit error rate was achieved at 100 km in the presence of atmospheric scintillation. At shorter ranges better than $10^{-6}$ bit error rate was achieved. Evaluation of link performance yielded results that were consistent predictions of performance based on analysis of scintillation effects. In addition, sustained periods of sufficiently low bit error rate were available for transmission of 3 channels of video data from the aircraft.

## 5.0 PROGRESS TOWARD SPACE SYSTEMS

The experience with AFTS through design, integration, and field operation has been significant in advancing both laser communications component and system maturity. The timely delivery of all components and operation of these components within specified requirements confirms hardware design approaches. Successful field operation of the lasercom system, meeting or surpassing all stated program objectives, verified the system engineering and analysis developed over the past 10 years. In total, the knowledge and experience gained from AFTS has moved laser communications into a posture for spaceborne applications.

### 5.1 Advances in Hardware Maturity

#### 5.1.1 High Data Rate Laser

The high data rate laser was developed as a space qualifiable prototype component. Through the development of this component a number of advances in laser technology were proven. The pure potassium pump lamp matched to the Nd:YAG absorption spectrum was one of the most significant. This lamp was the result of a long term development effort to devise the most efficient pump with mission compatible lifetimes. Seven iterations of lamp development were made resulting in a design which provided efficient, stable pumping, survived launch environment, and exceeded the contract lifetime goal of 3000 hrs. The experience gained in the areas of materials and processes and thermodynamics is relevant to subsequent Nd:YAG laser designs. During aircraft operation it was determined that excessive laser output beam motion resulted in degraded communications and acquisition performance. On AFTS this was corrected by incorporating an angular alignment correction loop in the interface optics. This correction technique is now being included in subsequent Lasercom system designs.

#### 5.1.2 High Data Rate Modulator

One improvement in the high data rate modulator was the change from Boron Nitride oven core material to a machinable glass-ceramic. This change eliminated the outgassing constituents which were degrading the crystal coatings and lowering transmission. Additionally, the fabrication process was restructured adding an annealing step to remove strain induced birefringence which was lowering extinction ratio. A pull test was added to the fabrication and test procedure to verify the

strength of the electrode solder bond. Transmission life tests have further verified the longevity of the modulator design incorporating these changes. These successfull developments in the space qualifiable prototype modulator represents one of the most significant technological advances of the AFTS program.

### 5.1.3 Imaging Optics Assembly

Development of the AFTS imaging optics assembly represents a significant advancement in laser communications system engineering. In addition to the special aspherics that were built for use with the APDs, system reliability was enhanced by building into the IOA both redundant and "back-up mode" optical paths. Combined with the flexibility of the microprocessor based DPA a number of real time system reconfigurations were possible to accommodate almost any performance anomaly from gimbal failure to multiple detector failures to TMBS failure.

Development of the diffraction limited Invar and Cer-Vit telescope was another AFTS program milestone. The inherent thermal stability of this design greatly reduced the cost of developing a telescope that could withstand the on orbit temperature extremes and maintain performance. Prior to AFTS, only an all Beryllium construction was considered due to stringent weight restrictions. The AFTS telescope was delivered weighing only a few pounds more than the all Beryllium counterpart in the EFM demonstrating that spaceborne systems designs might consider less costly materials for a small weight penalty.

Still another area of development in the AFTS IOA was in the design of the mechanisms used to select the various light paths through the assembly. The development effort had been driven by poor performance of the mechanisms used on the EFM IOA. Both systems required very short transition times to elminate or reduce interruptions in the transmit or receive light path. The EFM unit derived the rapid transition time by simply increasing the electromechanical drive force. Unfortunately, although the transition times were short, the mechanical energy required to achieve those times was detrimental to the system. The mechanical impact at the end of travel of the devices often was sufficient to stimulate high order vibrations in the system which disrupted performance, and caused a high failure rate in the mechanisms itself. The AFTS approach was to employ a force controlled mechanism design that was able to obtain extremely short transition

move and settle times by virtue of preloading. The mechanisms pivot points were all preloaded with flex-pivots so that the addition of a very small electro-mechanical force would change the preload balance and rapidly move the mechanism. The motion at the end of travel was damped with a precisely balanced combination of hard and soft stops. Initially, the performance of the mechanisms met all goals, meeting both transition time requirements, and move and settle limitations. However, despite careful design, some of these devices began to fail after a limited number of operations due to excessive side loading on the flex pivots. Although the flight test success was not hindered by this problem due to the backup capabilities designed in the system, the results on AFTS point out that additional design and testing is needed on mechanism development on future systems. The approach being developed on current operational systems is for a more simple mechanism design built around a highly reliable actuator using magnetic damping.

Aside from the problem of mechanisms, however, the AFTS IOA did demonstrate that flight worthy hardware could be built in a volume and weight allotment very close to that of the EFM and suitable for space systems. The packaging technique afforded extremely high packaging densities that are required for spaceborne systems.

5.1.4 Acquisition and Tracking System

During the SFTS/AFTS program a number of new techniques and technologies were incorporated into the system. At the outset those changes were incorporated either to reduce the risk in a spaceborne environment or to minimize size, weight, and power. It was intended, however, that the performance of the new designs be equivalent or better than the demonstrated EFM performance. Through rigorous analysis and tesitng each change was incorporated into the system design. Table 5.1-1 enumerates some of the more significant changes.

Table 5.1-1
Changes Between AFTS and EFM
Acquisition & Tracking System

1. Replaced PMT Acquisition Detectors with APDs
   Advantage: Lower Risk
   Reduced size, weight, and power

2. Replaced optical shaft encoders in gimbals with 20 bit Inductosyns®
   Advantage: Higher Reliability of Inductosyns for lower risk

3. Replaced Hybrid Analog/Digital Gimbal Control implementation with digital control loop
   Advantage: Reduced size, weight, and power
   Improved control loop optimization

4. Replaced hardwire mode logic with fully programmable microprocessor based mode logic control.
   Advantage: Reduced size, weight and power
   Reduced risk - added flexibility accommodated numerous back-up modes and manual overrides.

(Inductosyn registered by Farrand Inc.)

The design of the acquisition and tracking system was to demonstrate acquisition handover in less than six seconds with simulated satellite dynamics, utilize a 300 Hz tracking control loop, and demonstrate tracking performance of better than 0.6 $\mu$rad, peak. in the laboratory. The AFTS system performance demonstrated during acceptance testing at MDAC-STL met or exceeded all of those goals. During flight testing, a mean acquisition time of 5.2 seconds from the WFD uncertainty field (±0.2°) to fine tracking was demonstrated. The design acquisition handover goal was verified with platform dynamics much worse than those associated with typical satellite platforms. In addition, experience with the system has indicated yet further improvements that will be incorporated into subsequent designs.

The first significant change to come out of AFTS experience is the elimination of the Fine Tracking Detector. This detector was retained in the AFTS/SFTS system even after the APD's were incorporated as acquisition detectors, because the uniformity, alignment and gain stability of the APD was not well understood. However, refinements of both the image dividing optics preceding the APDs, and the APD and biasing control improved the performance capabilities in all of those areas. Performance during air-to-ground testing demonstrated equivalent tracking performance with either the APD NFD or the Silicon Quadrant Fine Tracking Detector.

The utility of software mode logic control was extremely beneficial during testing when it was necessary to select an alternative operating mode to overcome the failure of a mechanism in the IOA. However, experience with the development of that software has led to the development of a slightly different software organization to facilitate development and debugging.

5.2 Conclusion

In total, a number of significant lessons learned were obtained from AFTS. These lessons are quite valuable and, fortunately, did not prevent highly successful flight tests. In fact, one should include in lessons learned the validation of many suppositions that have now become fact in laser communications system design. The success of the program derived from the fact that enough lessons were learned before and during the design of the AFTS that only residual problems were left to be resolved during the flight tests.

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